Vol. XCIII. No. 6. November–December, 1956

GEOLOGICAL MAGAZINE

Edited by

O. M. B. BULMAN, S. R. NOCKOLDS, and W. B. HARLAND

assisted by

PROFESSOR W. G. FEARNSIDES PROFESSOR O. T. JONES
PROFESSOR LEONARD HAWKES PROFESSOR W. J. PUGH
PROFESSOR C. E. TILLEY

CONTENTS

PAGE

WILKINSON, J. F. G. The Olivines of a Differentiated Teschenite Sill Near Gunnedah, New South Wales 441
CULLEN, D. J. Pretoria Series Formations Near Kanye in the Bechuanaland Protectorate 456
PALLISTER, J. W. Slope Form and Erosion Surfaces in Uganda . . 465
HENSON, F. A. Contact Phenomena from N.W. Jersey, C.I. . . 473
COLEMAN, A. The Terrace Sequence at Dale-I-Sunnfjord . . . 485
HUMPHREYS, D. W. Some Problems of Size and Sorting in Sands . 491
MCKERROW, W. S., S. R. TAYLOR, A. L. BLACKBURN, and L. H. AHRENS. Rare Alkali Elements in Trilobites 504

CORRESPONDENCE

The Origin of Garnets in the Borrowdale Volcanic Series . . . 516
The Ammonite Genera *Arnioceras* and *Coroniceras* Hyatt . . . 517
Steinerina Hudson, nom. nov. 518

PUBLICATIONS RECEIVED
pp. 519–20

ANNOUNCEMENT
p. 520

INDEX
pp. 521–4

STEPHEN AUSTIN & SONS, LTD.
CAXTON HILL, WARE ROAD, HERTFORD, HERTS

SUBSCRIPTION 40/- PER ANNUM

GEOLOGICAL MAGAZINE

founded in 1864

by the late Dr. H. Woodward, F.R.S., with which

is incorporated

THE GEOLOGIST

(founded 1858)

Published every two months, price 45/- per annum
(single numbers, 10/-).

Subscriptions for 1956, inquiries relating to back stock, advertising, etc., should be sent to Stephen Austin & Sons, Ltd., Caxton Hill, Ware Road, Hertford, Herts.

The Editors are directed to make it known to the public that the authors alone are responsible for the facts and opinions contained in their respective papers and for the correctness of their references.

Instructions to Contributors.

Articles submitted for publication in the *Geological Magazine* should be addressed to the Editors at the *Sedgwick Museum, Cambridge*, not to the Publishers.

Manuscripts should be typewritten, double-spaced, and preferably with a wide margin, and should be carefully revised; they should be as concise as possible and should not exceed 10,000 words. In the case of a long article allowance must be made for text-figures at the rate of approximately twenty words per sq. in. MS. must be accompanied by a short abstract, 50–100 words. References should not be given in footnotes, but arranged in alphabetic order of author's names at the end of the article; the author's name should be followed by date of publication, and the title of each paper should be given in addition to volume and page numbers of the Journal, thus:—

LAPWORTH, C. 1878. The Moffat Series. *Quart. Journ. Geol. Soc.*, xxxiv, 240–343.

References should be cited in the text by author's name and date, with page reference if necessary, in brackets:—(Lapworth, 1878, p. 339).

Illustrations should be so drawn as to allow reduction to a maximum size of $6\frac{1}{2} \times 3\frac{1}{4}$ inches (the type-area of the Magazine) and originals must not exceed 40 × 22 inches. Map lettering should be such as to be clearly legible after reduction (equivalent to 5-point as a *minimum* on reduction), while lettering on text-figures should in general be left in pencil for printing.

Authors will receive 25 reprints free of cost.

GEOLOGICAL MAGAZINE

VOL. XCIII. No. 6. NOVEMBER–DECEMBER, 1956

Issued 7th December, 1956

The Olivines of a Differentiated Teschenite Sill Near Gunnedah, New South Wales

By J. F. G. WILKINSON

ABSTRACT

Data is presented on textural variation, optical properties, and resultant compositions of the olivines from a differentiated teschenite sill. The range in olivine composition is from Fa_{21} to Fa_{60}. Both the individual crystals and successive crops of crystals become more fayalitic with progressive differentiation.

INTRODUCTION

THIS paper presents the results of an investigation of the olivines from the Black Jack teschenite sill, a differentiated intrusion possessing a diameter of one mile and a thickness of approximately 500 feet. The intrusion is situated about four miles south-west of the township of Gunnedah, 200 miles north-north-west of Sydney, and 250 miles distant by rail.

The investigation embodies a study of the optical properties and resultant compositions of the olivines from nearly sixty teschenite specimens representative of the sill. These specimens were collected on five radial sections up the face of the intrusion (specimen numbers A to E) and on traverses across the roof (specimen numbers F to I). In the former instance, the approximate heights in feet of the specimens above the lower contacts are given (Table 2). Specimens F to I may be considered as occurring generally at heights of 440 to 500 feet above the lower contacts. The most olivine-rich facies (B1) contains 23 per cent modal olivine. The modal olivine decreases with decreasing height in the intrusion.

This study was carried out in the Department of Mineralogy and Petrology, Cambridge, and forms part of a petrological, mineralogical, and geochemical investigation of undersaturated basic alkaline magma undergoing progressive differentiation under hypabyssal conditions. In a subsequent paper the locations of the specimens studied will be indicated on a contoured geological map of the intrusion.

Optical Procedures, Accuracy of Resultant Compositions, and Some Mineralogical Implications

Refractive Indices.—Refractive indices, regarded by many workers as the most reliable optical property to obtain olivine compositions, were determined on suitably orientated grains by the immersion method. Care was taken to select grains with fresh clean-cut, straight, and moderately thin edges. A drop of the matching immersion liquid was transferred immediately by capillary to a refractometer, and its refractive index read, necessary precautions being taken to minimize temperature variations. An Abbe type refractometer was used for those refractive indices less than 1·740. For higher values, a Leitz-Jelley instrument was used. The accuracy of individual refractive index measurements is regarded as $\pm$ 0·002 $\sim$ 1 molecular per cent Fa.

Emphasis was placed on a knowledge of the composition of *average* olivine crystals of the most representative generation. To attain this end the refractive indices were determined on grains (wholly or partially removed) at the margins of uncovered thin sections, after preliminary microscopic examination (in terms of average grain-size, relationship to the rock fabric, in conjunction with a knowledge of the optical orientation) had established that the measurements were being made as far as possible on representative material. Removal of the grains as described above is especially useful in overcoming orientation difficulties in the olivines, due to the general absence of a well-defined cleavage, especially at the magnesian end of the series. After removal from the slide, all grains were well-washed in xylol and dried, before immersion in the refractive index liquids.

The β refractive index was most frequently determined, as sections with the point of emergence of an optic axis near the centre of the field are easily recognizable and relatively numerous. Due to the presence of relatively strong olivine zoning, the refractive indices were measured as far as possible across the unzoned central portions of the crystals, as were also the optic axial angles used for compositional purposes.

Optic Axial Angles.—All determinations of the optic axial angle were carried out on a Leitz 4-axis Universal Stage. Conventional optical procedure was observed in mounting the thin-section on the stage. Wherever possible, the consoscopic method of Hallimond (1950) was used in the determination of 2V. Where a direct determination of 2V could be carried out across the points of emergence of the optic axes in sections in which the acute bisectrix was approximately vertical, the mean of four separate settings for two positions 90 degrees apart was taken as the optic axial angle of the crystal, after necessary refractive index corrections had been made. The error

involved in 2V determinations by this method is probably $\pm$ 1 degree (cf. Fairbairn and Podolsky, 1951, p. 823).

It is necessary, however, to carry out 2V determinations on a number of grains in the one specimen. This was restricted by the limited number of suitably orientated grains ($\perp$ Bx_a), even using a number of thin sections from the one specimen. In addition, the presence of highly magnesian olivines with a large 2V, which results in high angles of rotation around A_4, discouraged direct determination of 2V, even using the conoscopic method. Consequently in the majority of cases, 2V was determined indirectly on suitably orientated grains from the position of one of the optic axes and a bisectrix (Bx_a). Fairbairn and Podolsky (1951, p. 828) consider this method accurate to $\pm$ 1 degree for minerals other than feldspars, high birefringence and thick sections tending to higher accuracy. It is believed that $\pm$ 2 degrees is a reasonable estimate of the order of accuracy, which may perhaps be increased in those instances where an average olivine 2V was taken as the mean value of determinations on several crystals in the one rock slice. The variation in composition of zoned olivines was measured most conveniently by 2V determinations on successive zones (cf. Tomkeieff, 1939, p. 234).

The determination of the optical properties of the olivines was carried out in sodium light at wave lengths of the yellow D lines.

Accuracy and Implications of the Compositions Derived from Optical Data

The compositions of the olivines expressed in terms of the molecular percentage of fayalite were derived from both the refractive index and mean optic axial angle values, read from the graphs of Poldervaart (1950, p. 1073). The final compositions (obtained as the mean of the two independent optical methods) refer to the average compositions of the central portions of crystals of the most widespread olivine fraction separating during the main crystallization period. These compositions as far as possible are not influenced by the compositions of minor second generation olivines or the presence of extreme zonal variation. The final compositions are regarded accurate to $\pm$ 2 molecular per cent of fayalite (cf. Poldervaart, 1950, p. 1068).

Since the teschenites from the upper levels of the sill carry modal olivine in small amounts, olivine compositions in these rocks were derived from refractive index determinations only (Table 3).

Certain conclusions emerge from the results of optical investigations of the olivines from the Black Jack intrusion (Table 2). These are as follows:—

(i) In general there is good correspondence in the compositions inferred from refractive index and 2V determinations. Compositional

differences between the two sets of values would average 1 to 3 molecular per cent Fa.

(ii) Moderately good agreement exists between the mean 2V (indirect measurement) derived from a number of olivines in the rock, and the optic axial angle obtained by direct measurement across the acute bisectrix.

(iii) Where noticeable discrepancies (greater than 3 molecular per cent Fa) do occur between the compositions obtained from the two optical measurements, no regular variation trend seems to exist. The optic axial angle values lie haphazardly above and below the β compositional values, usually regarded as the more reliable optical property. Such discrepancies may be due in part to the limitations of the methods employed, but it is believed that they stem mainly from two factors, namely:—

(*a*) The presence of olivine crystals of differing generation, which possess compositional differences.

(*b*) The presence of zoning in the olivines. Hence a crystal of apparently representative type may be observed as a result of the section being cut through the more fayalitic margins of an occasional zoned phenocryst.

Data illustrating the latter point is set out in Table 1. The β refractive indices, measured in each case across the centre of the grain, were obtained after microscopic examination of the olivines had suggested they were of representative type. It can be seen that 2V determinations of the olivines in a particular slice may show variations of 7 to 8 degrees, even before allowance is made for the accuracies of the method adopted.

Game (1941, p. 14), Frankel (1943, p. 8), and Johnston (1953, p. 166) have all found discrepancies in 2V determinations of olivines by measurement over both α and γ, $2V_\alpha$ being less than $2V_\gamma$.

In the Breven dolerite dyke, Krokström (1932, pp. 256–8) found variations in the optic axial angles of olivines whose densities appeared to be constant. In one slice nine crystals showed a range in 2V of 75 to 88 degrees. Neglecting the extreme values, the mean 2V (82 degrees) agreed fairly well with the 2V corresponding to the measured refractive indices (81 degrees). Krokström thought that the extreme values at least were due to some methodical error. Gjelsvik (1952, pp. 72–3) has also found variation in the 2V of olivines from the one specimen. By analogy with the presence of high and low temperature plagioclase, he suggested the possible existence of "high" and "low" olivine, the former variety being characteristic of rocks rapidly chilled from high temperatures. The same writer quotes in support of his views the experiments of Chudoba and Frechen (1943) who heated and quenched natural olivine crystals,

with a resultant decrease in 2V of 3 to 4 degrees. According to these authors (op. cit., p. 101), it is essential to make a number of optic axial angle measurements to obtain even an approximate knowledge of the olivine composition, and that the highest value of 2V should give the best approximation.

The search for higher accuracy in the olivine series is a difficult one, and it is probably unwise to quote compositions to 0·5 molecular per cent Fa, if such compositions are based solely on optical measurements. Moreover, a bulk chemical analysis need not necessarily represent accurately the composition of a given crystal under the microscope. In particular, the presence of zoning, particularly in

TABLE 1

VARYING OPTICAL DATA ON APPARENTLY REPRESENTATIVE OLIVINES

Rock Specimen	Refractive Indices	Composition (Mol. per cent Fa)	2V Inferred from Column II
A5	$\beta = 1{\cdot}760$	Fa_{31}	$2V(-) = 72$
	$\beta - 1{\cdot}770$	Fa_{36}	$2V(-) = 69$
I2	$\beta = 1{\cdot}710$	Fa_{29}	$2V(-) = 82$
	$\beta = 1{\cdot}745$	Fa_{45}	$2V(-) = 75$
C2	$\beta = 1{\cdot}708$	Fa_{27}	$2V(-) = 83$
	$\beta = 1{\cdot}725$	Fa_{35}	$2V(-) = 79$
C3	$\beta = 1{\cdot}710$	Fa_{29}	$2V(-) = 82$
	$\beta = 1{\cdot}721$	Fa_{33}	$2V(-) = 80$

rocks of alkali olivine-basalt parentage, should be critically evaluated. The possible existence of "high" and "low" olivines can be substantiated after detailed investigations have been carried out, embodying in particular the careful integration of zoning, presence of inclusions, differing olivine generations, and so on.

GENERAL FEATURES OF THE OLIVINES FROM THE BLACK JACK SILL

Despite a complete gradation in grain-size of the olivines occurring up to 450 feet above the lower intrusion contacts, two distinct and differing size groups can generally be recognized, the most representative group averaging 0·3 × 0·3 mm. The larger olivines (up to 1·5 × 0·7 mm.) are frequently idiomorphic short columnar, with the {021} form well developed. Elongation, generally not marked, is parallel to the "c" crystallographic axis. The smaller olivines are

frequently rounded and give the appearance of being slightly resorbed, such an appearance being due to either the partial marginal alteration to bowlingite or iddingsite, or the crystal outlines being determined by the interference of slightly earlier adjacent plagioclase laths. Microscopic data on several hundred olivines reveals that over 50 per cent of the olivines of both size groups are sub-ophitically indented by adjacent feldspar. Whilst the olivine as a rule crystallized in advance of the plagioclase, the latter mineral apparently solidified before the olivines (especially the smaller individuals) completed, or in certain instances, began their crystallization.

However, abnormality of habit is best exhibited by those olivines in the coarser-grained gabbroic teschenites characteristic of the upper 50 feet of the sill. In these rocks, optically continuous aggregates of sub-ophitic olivine up to $6{\cdot}0 \times 4{\cdot}0$ mm. are present, recalling similar types described by Walker (1930, p. 366) and Johnston (1953, fig. 1) from the upper crinanites of the Garbh Eilean sill. Where the olivines occur in this manner, they are markedly more fayalitic (Fa_{50}–Fa_{60}) than those varieties with a more normal habit occurring at similar levels in the intrusion (Fa_{35}–Fa_{45}) and assume a pale yellow tinge. These minerals occupy a later position in the crystallization sequence than those olivines in the lower levels of the sill. The presence of feldspar indentations and the sub-ophitic character in the whole range of compositions (Fa_{21}–Fa_{60}) is a feature of the Black Jack olivines. Whilst sub-ophitic olivines are not uncommon in rocks of tholeiitic parentage, they are usually confined to the more fayalitic members of the series (Krokström, 1937, p. 129; Wager and Deer, 1939, p. 75; Walker and Poldervaart, 1949, p. 633).

In some of the upper gabbroic teschenites, the olivine possesses marked elongation, in this case parallel to "a". Such "sliver" olivines may measure $2{\cdot}9 \times 0{\cdot}01$ mm. and are frequently grouped with a parallel or only slightly divergent arrangement. Similar prismatic olivines elongated parallel to "a" have been recorded by Kuno (1950, p. 970) in the Hakone lavas, but they appear to be more characteristic of undersaturated basic alkaline rocks. Thus they have been described by Browne (1927, p. 378) in a theralite from Bombala, New South Wales; by Marshall (1912, p. 306) in certain New Zealand olivine-nephelinite pegmatoids; in Lugar Sill theralites (Tyrrell, 1948, p. 169), and in Dunedin mugearites by Benson and Turner (1940, p. 197). In an earlier account of the New Zealand basic rocks similar olivines had been described as "hypersthene" on account of this unusual habit (Benson and Turner, 1939, p. 64). Turner (in Benson and Turner, 1940) has summed up the unusual features of olivines of this type.

Numerous octahedral iron-ore inclusions, with little evidence of

TABLE 2.—OPTICAL AND COMPOSITIONAL DATA ON THE OLIVINES AT VARIOUS HEIGHTS IN THE BLACK JACK INTRUSION

Specimen Number	Height in Feet above Lower Contact	Mean 2V of Olivine (± 1–2 degrees)	No. of Olivines Measured	2V on Olivine Directly (± 1 degree)	Composition from 2V (Mol. per cent Fa)	Refractive Indices (± 0·002)	Composition from R.I's (Mol. per cent Fa)	Mean Composition (Columns VI and VIII)
A1	40	2V = *87 (−)	6	—	Fa_{10}	$\beta = 1{\cdot}704$	Fa_{23}	Fa_{22}
A2	140	84	5	84	Fa_{25}	$\beta = 1{\cdot}713$	Fa_{29}	Fa_{27}
A3	340	81	4	79	Fa_{32}	$\beta = 1{\cdot}729$	Fa_{36}	Fa_{34}
A4	370	79	2	—	Fa_{36}	$\beta = 1{\cdot}731$	Fa_{38}	Fa_{37}
A5	440	72	4	—	Fa_{50}	$\beta = 1{\cdot}772$	Fa_{47}	Fa_{48}
B1	20(?)	87	6	85	Fa_{19}	$\beta = 1{\cdot}698$	Fa_{23}	Fa_{21}†
B2	20	83	7	—	Fa_{27}	$\beta = 1{\cdot}710$	Fa_{28}	Fa_{28}
B3	120	83	7	—	Fa_{27}	$\beta = 1{\cdot}714$	Fa_{30}	Fa_{29}
B4	270	82	10	78	Fa_{30}	$\beta = 1{\cdot}716$	Fa_{31}	Fa_{31}
B5	300	80	4	—	Fa_{34}	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{34}
B6	400	80	12	80	Fa_{34}	$\beta = 1{\cdot}728$	Fa_{36}	Fa_{35}
B7	420	80	9	—	Fa_{34}	$\beta = 1{\cdot}733$	Fa_{39}	Fa_{37}
B9	500	72	4	72	Fa_{50}	$\beta = 1{\cdot}761$	Fa_{52}	Fa_{51}
C1	60	83	7	81	Fa_{27}	$\beta = 1{\cdot}695$	Fa_{21}	Fa_{24}
C2	300	82	10	84	Fa_{30}	$\beta = 1{\cdot}714$	Fa_{30}	Fa_{30}
C3	315	80	7	81	Fa_{34}	$\beta = 1{\cdot}718$	Fa_{32}	Fa_{33}
C4	360	79	9	80	Fa_{36}	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{35}
C5	400	77	7	76	Fa_{40}	$\beta = 1{\cdot}730$	Fa_{37}	Fa_{39}
C6	440	76	5	76	Fa_{42}	$\beta = 1{\cdot}732$	Fa_{39}	Fa_{40}
C7	460	76	4	75	Fa_{42}	$\beta = 1{\cdot}732$	Fa_{39}	Fa_{40}
C9	480	75	4	—	Fa_{44}	$\beta = 1{\cdot}742$	Fa_{43}	Fa_{44}
D1	50	2V = 85	5	85	Fa_{32}	$\beta = 1{\cdot}709$	Fa_{27}	Fa_{30}
D2	80	84	6	—	Fa_{25}	$\beta = 1{\cdot}713$	Fa_{29}	Fa_{27}
D3	180	84	7	—	Fa_{25}	$\beta = 1{\cdot}710$	Fa_{25}	Fa_{25}
D4	220	81	9	80	Fa_{31}	$\beta = 1{\cdot}712$	Fa_{29}	Fa_{30}
D5	330	81	5	—	Fa_{31}	$\beta = 1{\cdot}718$	Fa_{32}	Fa_{32}
D6	365	80	4	80	Fa_{33}	$\beta = 1{\cdot}721$	Fa_{33}	Fa_{33}
D7	380	79	2	—	Fa_{36}	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{35}
D9	400	76	4	81	Fa_{42}	$\beta = 1{\cdot}736$	Fa_{40}	Fa_{41}
E1	90	84	4	84	Fa_{25}	$\beta = 1{\cdot}700$	Fa_{23}	Fa_{24}
E2	190	86	6	—	Fa_{21}	$\beta = 1{\cdot}709$	Fa_{27}	Fa_{24}
E3	210	83	4	82	Fa_{25}	$\beta = 1{\cdot}710$	Fa_{25}	Fa_{25}
E4	350	81	8	80	Fa_{31}	$\beta = 1{\cdot}714$	Fa_{30}	Fa_{31}
E5	350	78	4	78	Fa_{40}	$\beta = 1{\cdot}732$	Fa_{39}	Fa_{39}
E6	350	79	5	—	Fa_{36}	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{35}
E7	390	82	4	82	Fa_{27}	$\beta = 1{\cdot}720$	Fa_{32}	Fa_{29}
E8	410	79	3	80	Fa_{36}	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{35}
E9	450	79	4	80	Fa_{36}	$\beta = 1{\cdot}727$	Fa_{36}	Fa_{36}

* NOTE.—All the olivines have a negative optic sign. † Composition of bulk olivine by analysis = Fa_{22}.
No measurable olivine in specimens B8 (460 feet), C8 (465 feet), D8 (390 feet), D10 (440 feet).

any regular orientation, are a feature of the olivines occurring up to heights of 350 to 400 feet above the lower contacts. The (010) cleavage tends to be more distinct in the more fayalitic types from the upper levels of the sill.

The Compositions of the Olivines

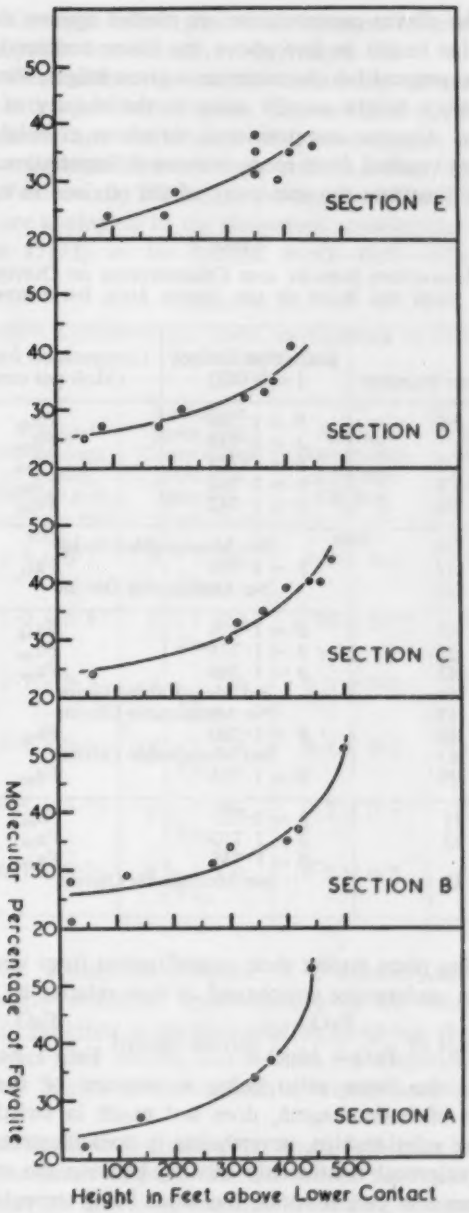
Optical data and compositions of the central portions of representative olivines at varying heights in the sill are set out in Table 2, whilst Table 3 contains data on the olivines from the roof of the sill. Variation in olivine composition with increasing height in the intrusion is represented graphically in Text-fig. 1.

The greatest variation in composition between the cores of individual crystals is from Fa_{21} to Fa_{60}, i.e. from chrysolite to hortonolite, following the nomenclature of Deer and Wager (1939). The average compositions of the earliest olivines crystallizing from the magma varies from Fa_{21} to Fa_{25}, figures comparable with the compositions of their counterparts in the Garbh Eilean (Fa_{17}), Palisades (Fa_{21}), and Dillsburg (Fa_{25}) sills, but slightly higher in their fayalite content compared with similar olivines in the New Amalfi sheet (Fa_{15}). The earliest olivine (Fa_{23}) from the theralitic Waihola sill, East Otago, reflects the abnormally ferruginous character of the parent magma (Benson, 1942, p. 169), being similar in composition to equivalent types (Fa_{24}) from the hypersthene-olivine-gabbros of the Skaergaard intrusion.

Up to heights of 300 feet from the lower contacts, the olivines changed only slightly in composition, from Fa_{23} to Fa_{32}. As differentiation speeded up and the successive magmatic liquids experienced more rapid compositional changes, the olivine compositions reveal more notable variation to Fa_{50} and in some instances in certain teschenites from the roof, to Fa_{60}.

The presence of two distinct olivine size groups suggests two generations, a feature borne out by refractive index measurements which indicate that the phenocrysts are consistently more magnesian than the olivines in the groundmass by 2 to 8 molecular per cent Fa (Table 4). The lower figure appears to be the more general. Compositional variation arising from differing olivine generations has been recognized in the Baltimore gabbro (Herz, 1951, p. 986), in Pacific lavas (Barth, 1931, p. 380), in the Palisades diabase (Walker, 1940, p. 1068), from the New Amalfi sheet (Poldervaart, 1944, p. 94), and from the Garbh Eilean sill (Johnston, 1953, p. 168).

Despite variation both in texture and the amount of modal olivine, the compositions of the olivines in general reveal no abrupt change (Text-fig. 1). The fayalite content is a function of the position of the mineral in the intrusion and increases with successively higher levels.



TEXT-FIG. 1.—Variation in composition with position of the olivines from the Black Jack Sill.

When all the olivine compositions are plotted against their positions in the sill (as height in feet above the lower contacts), it is found that a given composition characterizes a given height, the composition range at such a height usually being in the vicinity of 4 molecular per cent Fa. Greater compositional variations at heights of 450 to 500 feet have resulted from more extreme differentiation.

The data illustrates the sensitivity of the olivines to compositional

TABLE 3

REFRACTIVE INDICES AND COMPOSITIONS OF OLIVINES FROM THE ROOF OF THE BLACK JACK INTRUSION

Specimen Number	Refractive Indices (± 0·002)	Composition from R.I's (Mol. per cent Fa)
F1	$\beta = 1{\cdot}706$	Fa_{26}
	$\beta = 1{\cdot}710$	Fa_{28}
F2	$\beta = 1{\cdot}724$	Fa_{34}
F3	$\beta = 1{\cdot}747$	Fa_{45}
F4	$\beta = 1{\cdot}742$	Fa_{43}
G1	No Measurable Olivine	
G2	$\beta = 1{\cdot}760$	Fa_{51}
G3	No Measurable Olivine	
H1	$\beta = 1{\cdot}778$	Fa_{60}
H2	$\beta = 1{\cdot}735$	Fa_{40}
H3	$\beta = 1{\cdot}740$	Fa_{42}
H4	No Measurable Olivine	
H5	No Measurable Olivine	
H6	$\beta = 1{\cdot}760$	Fa_{51}
H7	No Measurable Olivine	
H8	$\beta = 1{\cdot}752$	Fa_{49}
I1	$\beta = 1{\cdot}727$	Fa_{36}
I2	$\beta = 1{\cdot}710$	Fa_{28}
	$\beta = 1{\cdot}745$	Fa_{44}
I3	No Measurable Olivine	

changes taking place during their crystallization from undersaturated basic magma undergoing enrichment in iron relative to magnesium. Whilst the plot of $\frac{FeO}{FeO + MgO}$ olivine against $\frac{FeO + Fe_2O_3}{FeO + Fe_2O_3 + MgO}$ parent rock, the latter ratio being a measure of the degree of fractionation of basic magma, does not result in strictly linear or smooth curve relationships, nevertheless it does illustrate in general the strong reciprocal relationship existing between the compositions of the olivines and parent rocks, the latter being strongly influenced by the amount of modal olivine. The Black Jack olivines are always richer in MgO and undergo stronger fractionation than the parent

rocks, and also experience greater enrichment in iron than the associated diopsidic titaniferous clinopyroxene.

The optical data illustrates complete miscibility between forsterite and fayalite at compositions between Fa[illegible] and Fa_{60}. In the tholeiitic New Amalfi sheet and the Skaergaard intrusion, gaps occur in the crystallization sequence between Fa_{47} and Fa_{80} and Fa_{50} and Fa_{60} respectively (Poldervaart, 1944, p. 94; Wager and Deer, 1939, p. 74). Such breaks are analogous to the theoretical considerations of Bowen and Schairer (1935) in the system MgO—FeO—SiO_2. In the

TABLE 4

COMPARATIVE COMPOSITIONAL DATA ON OLIVINES OF DIFFERING GENERATION

Specimen Number	Average Dimensions of Olivine Phenocrysts	Refractive Index and Composition (Mol. per cent Fa)	Average Dimensions of Smaller Olivines	Refractive Index and Composition
	mm.		mm.	
B1	1·6 × 0·7	β = 1·692 Fa_{19}	0·3 × 0·3	β = 1·701 Fa_{24}
D3	1·0 × 0·8	β = 1·710 Fa_{28}	0·35 × 0·35	β = 1·726 Fa_{35}
D4	1·1 × 0·7	β = 1·710 Fa_{28}	0·3 × 0·3	β = 1·714 Fa_{30}
D9	1·3 × 0·6	β = 1·736 Fa_{40}	0·4 × 0·3	β = 1·748 Fa_{46}
F1	0·75 × 0·75	β = 1·706 Fa_{26}	0·3 × 0·3	β = 1·710 Fa_{28}
F4	0·7 × 0·7	β = 1·739 Fa_{41}	0·3 × 0·3	β = 1·742 Fa_{43}

teschenites, the widespread presence of a microcrystalline undersaturated alkaline residuum approximating in its composition to analcite-syenite prohibits a reaction relation involving the formation of orthopyroxene from olivine, and restricts the magmatic liquids to that field where olivine of continuously changing composition alone precipitates.

Like the Garbh Eilean intrusion, the Black Jack mass is a product of alkali olivine-basalt magma. The olivines of the former intrusion apparently form an unbroken sequence from Fa_{19} to approimxately Fa_{97} (Johnston, 1953). The composition of the olivine cores 395 feet from the base of the Garbh Eilean sill (Fa_{43}) is comparable with the

average composition of the olivines from the upper levels of the Black Jack intrusion.

Several interesting features arise concerning the compositions of olivines whose relations to the general rock fabric differ from those commonly observed.

(i) In Table 5, comparison is made between those olivines poecilitically enclosed in clinopyroxene and the average olivine compositions in the rock. Except in the case of A1, the poecilitic olivine in every instance is slightly more forsterite-rich than the average olivine of the rock.

(ii) Specimen D9, 400 feet above the lower contacts, contains a contact between coarse-grained gabbroic teschenite and the finer-grained variety characteristic of the bulk of the sill. Compositional data on sub-ophitic olivines of similar dimensions in both rock types, but separated by a distance of 2 to 3 centimetres, are as follows: olivine of coarse phase $\beta = 1{\cdot}770$ Fa_{56}; olivine of normal teschenite $\beta = 1{\cdot}760$ Fa_{51}. The more fayalitic nature of the pegmatitic olivine

TABLE 5

COMPARATIVE COMPOSITIONAL DATA ON OLIVINES ENCLOSED IN CLINOPYROXENE

Specimen Number	Refractive Indices of Olivine in Pyroxene	Composition (Mol. per cent Fa)	Average Composition of Olivines of Rock
A1	$\beta = 1{\cdot}704$	Fa_{25}	Fa_{22}
B2	$\beta = 1{\cdot}708$	Fa_{27}	Fa_{23}
D3	$\beta = 1{\cdot}708$	Fa_{27}	Fa_{27}
D4	$\beta = 1{\cdot}706$	Fa_{26}	Fa_{30}
E9	$\beta = 1{\cdot}723$	Fa_{34}	Fa_{36}
I2	$\beta = 1{\cdot}712$	Fa_{29}	Fa_{44}

is analogous to the degree of iron enrichment shown by the minerals of tholeiitic dolerite pegmatites which lie further along the differentiation path than the parent rock (Walker, 1953, p. 52).

(iii) Whilst the bulk of the optical data is generally consistent with a more fayalitic olivine at successively higher levels, the compositions of certain olivines from the central portions of the roof of the intrusion (e.g. F1 and 12, Table 3; composition range Fa_{26}–Fa_{36}) are more magnesian than would be expected from their position. Such anomalous compositions may have resulted from relatively magnesia-rich pulses of magma being injected into the core of the sill at a late stage in its differentiation history. Olivines of comparable

composition occur at the highest point of the Garbh Eilean sill (Johnston, 1953, p. 170).

The study of the olivine compositions in the Black Jack sill strongly supports the conclusions of Tomkeieff (1939, pp. 243–4) and is in harmony with the crystallization processes as outlined by Bowen and Schairer, namely that the crystallization trend of olivines in igneous rocks on the whole follows the course from forsterite to fayalite. Both the individual crystals and the successive crops of crystals become more ferruginous with progressive crystallization.

Zoning in the Olivines

Zoning in thin section is shown by the olivines throughout the 500 feet of the sill. Data indicating the range of zoning, together with the average composition of the central portions of the crystals,

Table 6
Comparative Compositional Data on Zoned Olivines at Various Heights in the Black Jack Intrusion

Specimen Number	Height in Feet above Lower Contact	2V Values on the Margins of Zoned Crystals (± 1–2 degrees)	Compositional Range of Zones (Mol. per cent Fa)	Mean 2V and Composition of the Central Portions of Average Olivines (see Table 2, Columns III and IX)*	
A1	40	2V = 85, 81, 73	Fa_{23}–Fa_{48}	2V = 87	Fa_{22}
A2	140	78, 78, 71, 70	Fa_{35}–Fa_{54}	84	Fa_{27}
A5	440	71	Fa_{52}	76	Fa_{53}
B2	20	84	Fa_{25}	83	Fa_{26}
B3	120	80, 76, 76, 72, 72	Fa_{34}–Fa_{50}	83	Fa_{19}
B5	300	66	Fa_{63}	80	Fa_{34}
B6	400	77, 71, 71, 70	Fa_{40}–Fa_{54}	80	Fa_{35}
B7	420	77, 77, 74, 73, 73	Fa_{40}–Fa_{48}	80	Fa_{37}
C1	60	80	Fa_{24}	83	Fa_{24}
C2	300	80, 76, 75, 75, 70	Fa_{34}–Fa_{54}	82	Fa_{30}
C3	315	82, 76, 70	Fa_{30}–Fa_{54}	80	Fa_{33}
C4	360	74, 72, 72	Fa_{46}–Fa_{50}	79	Fa_{35}
C6	440	71	Fa_{52}	76	Fa_{40}
D5	330	75, 70	Fa_{44}–Fa_{54}	81	Fa_{33}
E2	190	85, 85, 81	Fa_{23}–Fa_{31}	86	Fa_{24}
E3	210	71	Fa_{52}	83	Fa_{29}
E4	350	80, 78	Fa_{34}–Fa_{38}	81	Fa_{31}
E5	350	76, 76	Fa_{42}	78	Fa_{38}
E6	350	78, 72	Fa_{38}–Fa_{50}	79	Fa_{35}
E7	390	80	Fa_{34}	82	Fa_{30}

* The average composition of the central portions of the olivines is the mean of the compositional values obtained from 2V *and* refractive index determinations.

is presented in Table 6. Excluding the small differences of 2 to 3 molecular per cent Fa between core and margin, the average compositional difference is of the order of 20 per cent Fa. Similar data on olivine zoning listed by Tomkeieff (1939, Table III) for British Carboniferous-Permian teschenites and essexites indicates differences of 15 and 17½ molecular per cent Fa between core and margin. The greatest range in composition measured on any one crystal (Fa_{34}–Fa_{62}) is not comparable with the greatest range in the Rapa luscladite olivines (Smith and Chubb, 1927, p. 319), namely Fa_{35}–Fa_{81} (Tomkeieff, 1939, Table II), or olivines from the upper crinanite of the Garbh Eilean sill, Fa_{30}–Fa_{87} (Johnston, 1953, p. 170). Occasional olivines in the Lake Waihola theralite are zoned from Fa_{34}–Fa_{69} (Benson, 1942, p. 164). Whilst the range in zoning appears to increase with increasing height in the Garbh Eilean sill, the greatest differences in zonal composition in the Black Jack olivines tend to occur in the minerals of the lower 350 to 400 feet of the intrusion.

In general, the more fayalitic rims of the zoned olivines are narrow, compared with the diameter of the crystals. About 25 per cent of the olivines examined on the Universal Stage show zoning. Consequently the bulk composition of the olivine from any specimen is not necessarily much more ferruginous than the average composition of the cores of the crystals, even though zonal studies on individual crystals may show a range of more than 20 per cent Fa. Thus, in B1, the average core composition is Fa_{31} (optics), compared with the bulk composition of Fa_{25} (chemical analysis). A study of the zoned olivines reveals that many of the sub-ophitic indentations by feldspar occurred in the final stages of crystallization when the iron/magnesia ratio of the residual magmatic liquids was undergoing rapid change. Thus, the feldspars may project into the zoned fayalitic margins but not into the more magnesia-rich core.

REFERENCES

BARTH, T. F. W., 1931. Mineralogical Petrography of Pacific Lavas. *Amer. Journ. Sci.*, xxi, 377–405, 491–530.

BENSON, W. N., 1942. The Basic Igneous Rocks of Eastern Otago and their Tectonic Environment, Part III. *Trans. Roy. Soc. N.Z.*, lxxii, 160–185.

—— and F. J. TURNER, 1939. Comparative Composition-Variation Diagrams for the Cainozoic Igneous Rocks of New Zealand, etc. *Trans. Roy. Soc. N.Z.*, lxix, 56–72.

—— —— 1940. Mugearites in the Dunedin District. *Trans. Roy. Soc. N.Z.*, lxx, 188–199.

BOWEN, N. L., and J. F. SCHAIRER, 1935. The system MgO.FeO.SiO_2. *Amer. Journ. Sci.*, xxix, 151–217.

BROWNE, W. R., 1927. Petrological Notes on some New South Wales Alkaline Basic Rocks. *Journ. Roy. Soc. N.S.W.*, lxi, 371–382.

CHUDOBA, K. F., and J. FRECHEN, 1943. Der Einfluss der Temperatur auf die Beziehung zwichen Optik and Chemiscus der Olivine. *N. Jb. Min. Geol. Pal. Monatsch.*, vi, 91–106.

DEER, W. A., and L. R. WAGER, 1939. Olivines from the Skaergaard Intrusion, Kangerdluqssuak, East Greenland. *Amer. Min.*, xxiv, 18–25.

EDWARDS, A. B., 1941. The Crinanite Laccolith of Circular Head, Tasmania. *Proc. Roy. Soc. Vict.*, liii, 403–415.

FAIRBAIRN, H. W., and T. PODOLSKY, 1951. Notes on Precision and Accuracy of Optic Angle Determination with the Universal Stage. *Amer. Min.*, xxxvi, 823–832.

FRANKEL, J. J., 1943. Studies on Karroo Dolerite—(2) Some Younger Intrusions of Olivine Basaltic Dolerite. *Trans. Geol. Soc. S. Africa*, xlv, 1–26.

GAME, P. M., 1941. Optical Properties of Olivines from Ubekendt Island, West Greenland. *Miner. Mag.*, xxvi, 11–15.

GJELSVIK, T., 1952. Metamorphosed Dolerites in the Gneiss Area of Sunnmøre on the West Coast of Southern Norway. *Norsk. Geol. Tiddsskr.*, xxx, 32–134.

HALLIMOND, A. F., 1950. Universal Stage Methods. *Min. Mag. Lond.*, lxxxiii, 12–22, 77–80.

HERZ, N., 1951. Petrology of the Baltimore Gabbro, Maryland. *Bull. Geol. Soc. Amer.*, lxii, 979–1016.

JOHNSTON, R., 1953. The Olivines of the Garbh Eilean Sill, Shiant Isles. *Geol. Mag.*, xc, 161–171.

KROKSTRÖM, T., 1932. The Breven Dolerite Dyke, a Petrogenetic Study. *Bull. geol. Instn. Univ. Upsala.*, xxiii, 243–330.

—— 1937. The Hällefors Dolerite Dyke and some Problems of Basaltic Rocks. *Bull. geol. Instn. Univ. Upsala*, xxvi, 113–263.

KUNO, H., 1950. Petrology of Hakone Volcano and the Adjacent Areas, Japan. *Bull. Geol. Soc. Amer.*, lxi, 957–1019.

MARSHALL, P., 1912. Nephelinite Rocks of New Zealand. *Trans. Proc. N.Z. Inst.*, xliv, 304–7.

POLDERVAART, A., 1944. The Petrology of the Elephant's Head Dike and the New Amalfi Sheet (Matatiele). *Trans. Roy. Soc. S. Afr.*, xxx, 85–119.

—— 1950. Correlation of Physical Properties and Chemical Composition in the Plagioclase, Olivine, and Orthopyroxene Series. *Amer. Min.*, xxxv, 1067–1079.

SMITH, W. C., and L. J. CHUBB, 1927. The Petrography of the Austral or Tubuai Islands (Southern Pacific). *Quart. Journ. Geol. Soc.*, lxxxiii, 317–340.

TOMKEIEFF, S. I., 1939. Zoned Olivines and their Petrogenetic Significance. *Miner. Mag.*, xxv, 229–251.

TYRRELL, G. W., 1948. A Boring through the Lugar Sill. *Trans. Geol. Soc. Glasgow*, xxi, 157–202.

WAGER, L. R., and W. A. DEER, 1939. Geological Investigations in E. Greenland, Part III : The Petrology of the Skaergaard Intrusion, Kangerdluqssuaq, East Greenland. *Medd. Grønland*, cv, 4, 352 pp.

WALKER, F., 1930. The Geology of the Shiant Isles (Hebrides). *Quart. Journ. Geol. Soc.*, lxxxvi, 355–398.

—— 1940. Differentiation of the Palisade Diabase, New Jersey. *Bull. Geol. Soc. Amer.*, li, 1059–1106.

—— 1953. The Pegmatitic Differentiates of Basic Sheets. *Amer. Journ. Sci.*, ccli, 41–60.

—— and A. POLDERVAART, 1949. Karroo Dolerites of the Union of South Africa. *Bull. Geol. Soc. Amer.*, lx, 591–706.

DEPARTMENT OF GEOLOGY,
THE UNIVERSITY OF NEW ENGLAND,
ARMIDALE, N.S.W.

Pretoria Series Formations Near Kanye in the Bechuanaland Protectorate

By D. J. Cullen

Abstract

At two localities near Kanye, in the south-eastern Bechuanaland Protectorate, formations previously assigned to the Waterberg System are now correlated with the Pretoria Series of the Transvaal System. In addition to modifying the palæogeography of the Transvaal period, this correlation may also help to clarify the stratigraphical position of the Matsap Series of the Cape Province.

Introduction

At Segwagwa and Dikgomo di Kae, near Kanye, in the south-eastern Bechuanaland Protectorate, recent mapping has proved the presence of rocks belonging to the Pretoria Series of the Transvaal System. The occurrence of Pretoria Series rocks in these areas is of considerable geological significance, as they lie between the large basins of Transvaal sediments in the Transvaal and northern Cape Province.

Table 1.—Standard Correlation of South African Proterozoic Formations

Time or Stage		Epoch or Series	Period or System	Era or Group
Cape	Transvaal			
		Matsap	WATERBERG	PROTEROZOIC
		Camagara	LOSKOP	
U. Griquatown M. Griquatown L. Griquatown	Smelterskop Magaliesberg Daspoort Timeball Hill	Pretoria Dolomite Black Reef	TRANSVAAL	
			VENTERSDORP	
			WITWATERSRAND	
			DOMINION REEF	

Based on " Table of Geological Formations of the Union of South Africa and South-West Africa ", Geological Survey, Pretoria, 1954.

Very little work had previously been carried out at either Segwagwa or Dikgomo di Kae, and the rocks occurring there were, until recently,

believed to be entirely of Waterberg age (du Toit, 1954, p. 210, and appended map).

The author is indebted to the Director of the Geological Survey, Bechuanaland Protectorate, for permission to publish this paper, and to Dr. S. H. Haughton for criticism and encouragement.

The Segwagwa Area.

Segwagwa Hill lies 20 miles south-west of Kanye, rising above a level plain which is largely covered by surface deposits of sand and calcrete. The rocks outcropping near Segwagwa can be matched, even in minor details of lithology and succession, with the Pretoria Series strata of the western extremity of the Bushveld basin at Lobatsi, 30 miles to the east. The Waterberg System is not represented at Segwagwa, and the nearest exposures of the distinctive red and purple quartzites and conglomerates of this age are at Kanye itself.

Lithology and Succession.

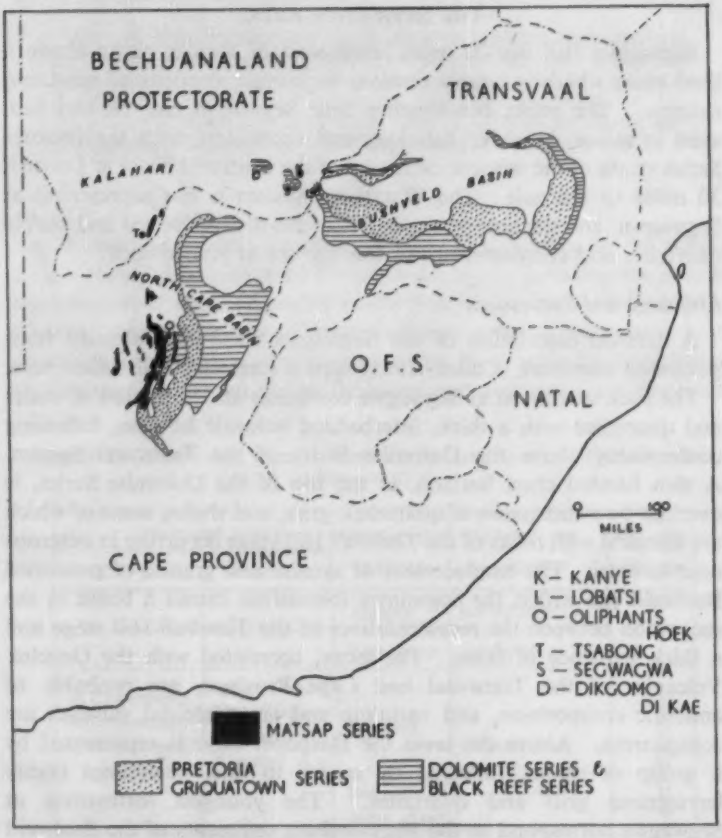
A detailed description of the Segwagwa rocks has already been published elsewhere (Cullen, 1955), and a summary will suffice here.

The rock succession at Segwagwa comprises an alternation of shales and quartzites with a thick, interbedded volcanic horizon, following conformably above the Dolomite Series of the Transvaal System. A thin banded chert horizon, at the top of the Dolomite Series, is overlain by a succession of quartzites, grits, and shales, some of which are identical with rocks of the Timeball Hill stage occurring in outcrops near Lobatsi. The emplacement of syenite and granite of presumed Bushveld age within the Segwagwa formations causes a break in the succession between the representatives of the Timeball Hill stage and a thick sequence of lavas. The latter, correlated with the Ongeluk Volcanics of the Transvaal and Cape Province, are probably of andesitic composition, and variolitic and amygdaloidal varieties are conspicuous. Above the lavas the Daspoort stage is represented by a group of shales, followed by coarse to fine, sometimes highly ferruginous grits and quartzites. The youngest formations at Segwagwa correspond to the Magaliesberg sediments of the Bushveld basin, and again consist of shales overlain by quartzites. As at Lobatsi, the Magaliesberg shales include siltstones, a characteristic dolomitic limestone, and, near the base, a band of black and striped cherts. Predominantly white and grey Magaliesberg quartzites form Segwagwa Hill itself.

Structure.

The most important structural feature of the area is the folding in two directions of the Pretoria Series strata. The axis separating the

two fold trends is directed north-north-west from Segwagwa Hill. The dominant folding is in a N.W.–S.E. direction, parallel to the regional trend and striking towards Dikgomo di Kae. West of Segwagwa Hill, however, the strike of the beds swings sharply through more than 90 degrees to N.N.E.–S.S.W. and N.E.–S.W. This trend



TEXT-FIG. 1.—General map of southern Africa showing the position of the Pretoria Series rocks near Kanye in relation to the Bushveld and North Cape basins.

is maintained westward for several miles in open-folded strata before calcrete surface deposits obscure the structure.

Widespread faulting has occurred in two directions. The major faults are aligned N.E.–S.W., while subsidiary faulting has occurred in an E.N.E.–W.S.W. direction. There is reason to suspect extensive tear-faulting in the vicinity.

Dikgomo di Kae Area

At Dikgomo di Kae, 50 miles west-north-west of Kanye, a series of quartzites alternating with shales rests, without any apparent unconformity, upon rocks of the Dolomite Series of the Transvaal System. The shales and quartzites closely resemble those of the Segwagwa succession, and are also correlated with the Pretoria Series. They are quite distinct from the typical red and purple Waterberg quartzites and conglomerates which overlie them with marked unconformity near Dikgomo di Kae Hill.

Lithology and Succession.

In the area under discussion, there is no evidence of banded cherts at the top of the Dolomite Series. The dolomite is succeeded by poorly exposed, platy, siliceous shales and micaceous shales, followed upwards by a well-defined horizon of grey and brown quartzites. These shales and quartzites are correlated with the Timeball Hill Stage of the Pretoria Series. The Daspoort Stage is represented by a group of shales with a thick sequence of interbedded dark, greenish lavas, overlain by a well-exposed quartzite horizon. The lavas are correlated with the Ongeluk Volcanics since immediately below them there is a greenish-grey pebbly "tillite" similar to that forming a widely distributed marker horizon in both the Transvaal and Cape Province. The Daspoort Quartzites are predominantly grey or white in colour, with some subordinate highly ferruginous bands. A horizon of peculiar black and banded cherts overlies the quartzites in the area immediately north of Dikgomo di Kae Hill. These cherts are identical with those occurring at the base of the Magaliesberg Shales at Segwagwa but they are thicker and much better exposed. The cherts are succeeded by grey shales and siltstones, while black graphitic shales occur in association with oolitic limestones. No representatives of the Magaliesberg Quartzites have as yet been encountered.

Structure.

Pre-Waterberg folding and faulting complicates the structure of the area. The Transvaal formations north of Dikgomo di Kae Hill have been folded into anticlines and basins with axes aligned approximately east–west. East of Dikgomo di Kae the Pretoria Series strikes south-eastward in the general direction of Segwagwa, but near the hill the trend changes and the beds strike west and west-south-west into the Kalahari.

The Transvaal formations have been dislocated by a number of N.E.–S.W. faults.

The Waterberg strata strike approximately east–west, with a moderate dip to the south, and they show little evidence of either folding or faulting.

Modification of the Palaeogeography of the Transvaal Period

Because of a remarkable similarity in lithology and succession, rocks outcropping at Segwagwa and Dikgomo di Kae are correlated with the Pretoria Series of the Bushveld basin. As it is considered unlikely that such similar formations would be deposited in separate basins, the first inference to be drawn from this correlation is the probability that sedimentation was continuous between the Bushveld basin and the south-eastern Bechuanaland Protectorate during the Transvaal period. Denudation of a broad, open anticlinal fold is all that would be required to expose the granite pluton which now intervenes between the two areas.

A. L. du Toit (1954, pp. 127 and 154) describes the Transvaal System rocks near Kanye as lying at the northern extremity of the North Cape basin. The latter appears to be generally considered as a discrete basin of sedimentation in which peculiar chemical and very fine clastic rocks of the Griquatown facies (now represented by ferruginous cherts and jaspers) were being deposited simultaneously with the strongly contrasting, coarser, cyclic sediments of the Pretoria Series in the Transvaal region. Du Toit (1954, p. 156) specifically mentions the development of typical Griquatown formations near Kanye, a statement which is not supported by the recent field-work.

It is not disputed, however, that sedimentation in the Kanye area during the Transvaal period was continuous with that in the northern Cape. On the contrary, it is envisaged that a single basin of sedimentation extended over the Transvaal, much of the southern Bechuanaland Protectorate and the northern part of the Cape Province throughout the Transvaal period. The difference in sedimentation between the Transvaal and Cape portions of such a basin could be attributed to different tectonic and geosynclinal environments.

A Suggested Correlation of the Matsap and Gamagara Series with the Pretoria and Loskop Formations

Rock formations at Dikgomo di Kae and Segwagwa, now correlated with the Pretoria Series, were formerly included in the Waterberg System (du Toit, 1954, p. 210). Although correlation of these formations with the typical Waterberg strata, as seen at Kanye, can no longer be considered, some very striking comparisons can be made with the Matsap Series of the Cape Province which, in standard correlation tables (Geol. Surv., Pretoria, 1954), is included in the Waterberg System. An attempt to explain the similarity of the Segwagwa and Dikgomo di Kae rocks to the Matsap Series on the one hand, and to the Pretoria Series on the other, has led to the suggestion that a correlation can be effected between the Matsap and

TABLE 2.—COMPARISON OF THE GRIQUATOWN AND MATSAP SERIES WITH THE PRETORIA AND LOSKOP FORMATIONS

CAPE PROVINCE		TRANSVAAL		
U. MATSAP	*Purple & red quartzites & grits with shales and phyllites.*	LOSKOP	*Purplish black shales & flagstones with red & purple sandstones. Formerly included in the Rooiberg Group.*	
		BUSHVELD IGNEOUS ACTIVITY.		
M. MATSAP	HARTLEY HILL VOLCANICS *Andesitic lavas & tuffs. Interbedded purple quartzites.*	PRETORIA SERIES	DULLSTROOM VOLCANICS *Andesitic lavas & agglomerates.*	
L. MATSAP	*Pink & white quartzites.*		Magaliesberg Group.	*Shale & quartzite (Smelterskop)*
	Shales with dolomitic limestones.			*Quartzites (white & grey).*
				Shales with dolomitic limestone.
U. GRIQUATOWN	LAVAS & TUFFS. *Shales & quartzites overlying cherts & jaspers.*			MACHADODORP TUFFS.
			Daspoort Group.	*Shales.*
M. GRIQUATOWN	ONGELUK VOLCANICS. *Tillite.*			*Quartzites.*
				Shales.
				ONGELUK VOLCANICS.
				Glacial Horizon.
				Shales.
L. GRIQUATOWN	*Jaspers & banded cherts.*		Timeball Hill Group.	*Quartzites & shales.*
DOLOMITE (CAMPBELL-RAND) SERIES.		DOLOMITE SERIES		*Banded chert & ironstone*
				Dolomitic limestones

Gamagara Series and the Pretoria and Loskop formations as summarized in Table 2.

The Break between the Griquatown and Matsap Formations.

In this correlation, much depends upon the significance of the break between the Upper Griquatown strata and the Lower Matsap. This break is normally supposed to involve a considerable time interval during which folding and denudation of the Transvaal formations were followed by a widespread transgression during the Matsap epoch (Truter and others, 1938, pp. 27–38). The presence of Griquatown jasper pebbles within the Matsap has been used as an argument in favour of a lengthy break. It is now suggested, however, that there is no necessity to consider the break between the Upper Griquatown stage and the Lower Matsap as having been of long duration. In the first place, the widespread overlap by the Matsap seems to be confined to red and purple arenaceous deposits of Upper Matsap type. There is little or no evidence that the shales and white quartzites of the Lower Matsap transgress, and, indeed in some areas (for example, at Oliphants Hoek), there is apparently no unconformity between them and the Upper Griquatown. Furthermore, pebbles of Griquatown jasper do not occur in the oldest beds—as opposed to the basal beds—of the Matsap Series, but appear only at higher horizons. It is well known that the Griquatown jaspers and cherts are merely the surface representatives of chemical and fine-grained clastic sediments, and that the latter are notoriously susceptible to silicification and oxidation under suitable weathering conditions (du Toit, 1954, p. 158). In the Middle Griquatown, jaspers were formed also by contemporaneous baking of sediments by the lavas (du Toit, 1954, p. 162).

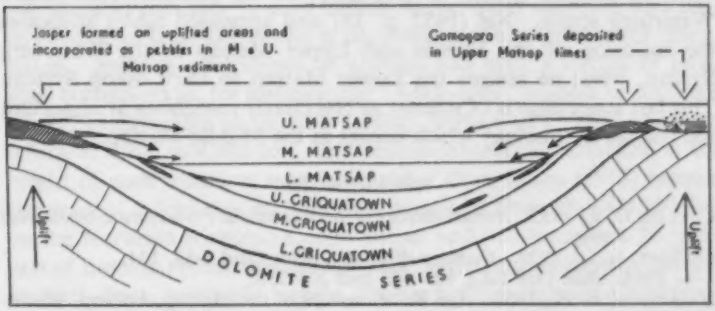
It is suggested, therefore, that, at the end of the Griquatown epoch, relatively gentle earth-movements exposed the Griquatown beds to sub-aerial weathering. Simultaneous with the deposition of the lowest Matsap strata, jasper was being formed as a surface " crust " on the uplifted areas, to be incorporated subsequently in the younger Matsap beds. Text-fig. 2 demonstrates that overstep combined with overlap can account for these conditions. Such phenomena are to be expected if the Matsap deposits are of geosynclinal origin as postulated by du Toit (1954, p. 206). As shown in Text-fig. 2, the Gamagara Series is interpreted as being a local facies of the transgressive Upper Matsap. The occurrence of reddish and purple quartzites in the Gamagara Series (Truter and others, 1938, p. 32) is considered to be significant, while the underlying thin shales may be equivalent to the sericitic phyllites of the Upper Matsap.

Lithological Comparisons.

The Matsap Series is in general included in the Waterberg System,

mainly on lithological grounds. It is true that the Upper Matsap sediments are of similar facies to the Waterberg strata, but, equally, they can be matched with the Loskop sediments of the Transvaal, described by Truter (1949, p. lxvi).

The Lower Matsap beds are quite unlike any occurring in the Waterberg System. The shales, containing dolomitic limestones and overlain by white quartzite, which characterize the Lower Matsap, contrast strongly with the normal Waterberg basal conglomerates and pebbly grits. Limestones are extremely rare in the Waterberg succession, while a volcanic horizon, equivalent to the Middle Matsap is unknown, with perhaps one possible exception in the northern Transvaal (du Toit, 1954, p. 212). On the other hand, the Lower Matsap beds do resemble those of the uppermost Pretoria Series described by D. G. L. Visser (1945, p. 207). Moreover, they seem to



TEXT-FIG. 2.—Schematic section illustrating the proposed interpretation of the relationship between the Matsap, Gamagara, and Griquatown Series. Overlap is combined with overstep.

continue the type of coarser sedimentation which was making its appearance towards the end of the Griquatown epoch. It is significant that du Toit (1939, p. 134) suggests a comparison of the Upper Griquatown strata with the Daspoort Stage of the Transvaal and this supports the possibility of the Lower Matsap being equivalent to the uppermost Magaliesberg beds.

In brief, it is envisaged that, towards the end of the Griquatown epoch, disturbance of the hitherto quiet conditions of sedimentation in the northern Cape Province caused a change of facies towards that which had predominated in the Transvaal area throughout the Pretoria epoch. This process continued with the deposition of passage beds during the Lower Matsap, and culminated in the widespread, uniform deposition of " red beds ", corresponding to the Loskop formations, in Middle and Upper Matsap times.

Significance of Dikgomo di Kae.

Du Toit (1954, pp. 204–5) considers the presence of Waterberg strata at Dikgomo di Kae to be an important link in the correlation of the Matsap and Waterberg formations. The recent discovery of Pretoria Series rocks at this locality, striking approximately westward, supports the alternative correlation of the Matsap with part of the Pretoria Series.

Previously Proposed Correlations.

Although the standard correlation tables still include the Matsap Series in the Waterberg System, considerable uneasiness has been apparent in recent years concerning this correlation. Taking into consideration the intense folding of the Matsap formations, Haughton (1950, pp. 205–8) has proposed that the latter should be correlated with the Loskop System in preference to the relatively little-folded Waterberg strata. Nel (1952, p. 357 and appended table) advocates the inclusion of the Middle and Upper Matsap in the Waterberg System, while he assigns the Lower Matsap to the Loskop System. This last suggestion is of interest as Nel clearly recognizes as important the change in lithology which occurs in the Middle Matsap.

REFERENCES

Cullen, D. J., 1955. *Annual Report of Bechuanaland Protectorate Geological Survey.*

du Toit, A. L., 1939. *Geology of South Africa* (2nd Ed.), 134.

—— 1954. *Ibid.* (3rd Ed.), 125–163 and 203–218.

Haughton, S. H., 1950. Age Relationships of the Matsap, Loskop, Waterberg and Nama Systems. *Trans. Geol. Soc. S. Afr.*, liii, 205–8.

Nel, L. T., 1952. Notes on the Correlation of the Geological Formations in the Union of South Africa and South-West Africa. XIX^{e} *Congres Géol. Internat.*, Fasc. xx, 353–9, and appended table.

Truter, F. C., 1949. A Review of Volcanism in the Geological History of South Africa. *Trans. Geol. Soc. S. Afr.*, lii, xxix–lxxxix.

—— *et al.*, 1938. *The Geology and Mineral Deposits of the Oliphants Hoek Area, Cape Province*, 27–38.

Visser, D. G. L., 1944. Stratigraphic Features and Tectonics of Portions of Bechuanaland and Griqualand West. *Trans. Geol. Soc. S. Afr.*, xlvii, 207.

Geological Survey, Pretoria, 1954. *Table of Geological Formations of the Union of South Africa and South West Africa.*

Geological Survey,
Lobatsi,
Bechuanaland Protectorate.

Slope Form and Erosion Surfaces in Uganda

By J. W. Pallister

Abstract

A preliminary analysis of slope forms in Buganda has indicated an erosional cycle characterized by both parallel scarp retreat and summit lowering, of which the latter process predominates in the later stages of the cycle. The recognition of characteristic stages in the erosional development of the landscape may provide a means of distinguishing a warped erosion surface occurring at differing altitudes from the products of separate erosion cycles.

Introduction

THE broad correlation of African erosion surfaces has been established by the comprehensive work of Dixey (1938, 1942, 1955), King (1951), and Cahen and Lepersonne (1952). In detail however, considerable difficulty is encountered in the local mapping and correlation of surfaces and bevels in the absence of sure criteria for recognition. Striking coincidence of altitude has been a means of large scale correlation as, for instance, the " 4,000-foot " Surface of southern Africa, recognizable as the mid-Tertiary Surface of Central and East Africa at 4,200 to 4,400 feet. But considerable local variations in the height of such a surface may be found. Thus, Dixey (1944) records the gradual fall of this mid-Tertiary peneplain from about 4,750 feet on the Northern Rhodesia-Congo border to 3,910 feet about 70 miles east of Lusaka. While this difference in height represents an extremely gradual slope, probably largely due to normal erosional processes, similar differences of altitude are caused elsewhere by relatively sharp warping or faulting, especially in the neighbourhood of the rift depressions. In such circumstances identification of separated remnants of erosion surfaces becomes obscure. The very rare occurrence of datable sediments on Mesozoic and Tertiary erosion surfaces precludes the more orthodox means of correlation. Where two or more sets of bevels occur at different altitudes but separated from each other, how is one to decide whether they are fragments of a warped, formerly continuous surface, or represent surfaces of different ages ?

Some assistance in solving such a problem may be gained from the study of the slope characteristics of the erosion surface remnants. A very considerable literature has accumulated on the subject of the origins and development of hillslopes. Reference may be made to a recent publication prepared for the International Geographical Congress meeting at Rio de Janeiro (1956). A local study of slope development in Buganda, the central province of Uganda Protectorate, (Pallister, 1956) has demonstrated remarkably permanent slope elements in the landscape. What is pertinent to the problem of dating

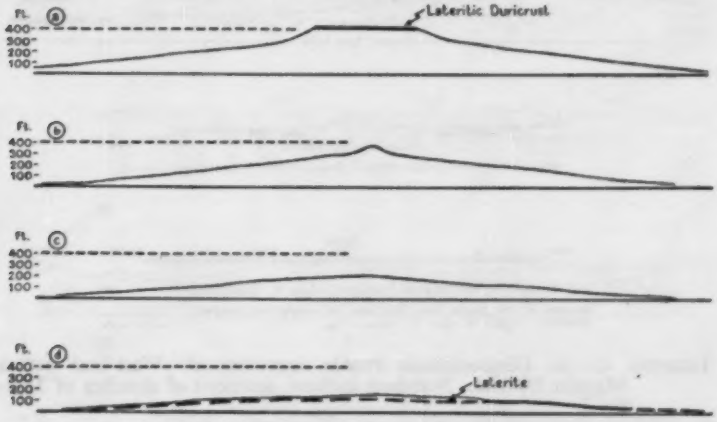
erosion surfaces is that these slope elements can indicate clearly the stage of development of a landscape and assist, therefore, in identifying separated remnants of the erosion cycles.

Evolution of Hillslopes

The very characteristic topography of Buganda is eroded from a series of granitic gneisses and meta-sediments with moderately even resistance to denudation. Relatively thin quartzite bands are more resistant, but are insufficient to exert a prominent influence on the general topography. Of much more importance is a strong capping of lateritic " duricrust " very thickly developed on the bevelled summits of the higher hills, and therefore considered to date from the time of maturity of the erosion cycle of which the hills are remnants. This has generally been considered to be mid-Tertiary. There is a tendency for these flat-topped hills to be formed of metasediments, while granitic or gneissose areas are of somewhat lower altitude with rounded hills generally lacking the lateritic capping, though they occasionally exhibit local pavements of laterite on their flanks. Two reasons may be advanced to explain the contrast: the original " duricrust " over granitic rocks may have been thinner or of a nature more easily eroded ; and under humid conditions granitic rocks have weathered chemically with greater ease than the metasediments. Feldspars in both groups of rocks are extensively kaolinized to a considerable depth.

The study of the slopes of both flat-topped and rounded hills has shown the existence of very characteristic slope elements, and the development of the erosion cycle can be recognized to take place mainly by the successive elimination of these elements in a manner quite consistent with that described by King in Southern Rhodesia and elsewhere. Briefly, they are *summit-flat*, *hillslope* (*sensu stricto*), and *pediment* (*piedmont*). Over two hundred clinometer readings have shown a close range of angles of inclination for the hillslope and pediment. (Text-fig. 1, *a*). Denudation takes place by parallel retreat of slopes until the summit flat with its protective " carapace " is reduced to a short, narrow ridge or, more commonly, a rounded cone. (Text-fig. 1, *b*). At this stage, when the laterite is reduced to a mass of rubble, lowering of the summit commences, with possibly some rise in the upper limit of the pediment, and a " pediment-dome " is formed by circus pediplanation (Mabbutt, 1955) (Text-fig. 1, *c*). A pediplain may now be said to be developed. (" The ultimate cyclic landform is the pediplain, consisting dominantly of broad coalescing pediments " —King, 1953). For a number of reasons, however, the pediments are somewhat steeper than normally encountered in arid or semi-arid landscapes and there remains a topography of low, broad, slightly concavo-convex hills with slopes showing a very constant angle of

inclination of about 5° to 7°. The subsequent evolution of the erosion cycle is extremely slow and progresses by interstream degradation and reduction of the angle of inclination of the pediments mainly by a process of soil creep (see also Dixey, 1956). Laterite formation appears to take place at or about the water-table which forms a very subdued interfluvial rise, and the presence of this hard layer of laterite within the weathered rock or subsoil provides the ultimate baselevel for the erosion cycle (Text-fig. 1, *d*). This final stage of very low domes of laterite with some residual soil at the summit is well exemplified in the larger residuals of the mid-Tertiary Surface (Pallister, 1954). It is important to note that summits may show a general coincidence of altitude throughout the cycle, but they do not themselves always



TEXT-FIG. 1.—Generalized Profiles of Hills in Buganda to illustrate stages in the erosion cycle. (Natural scale).

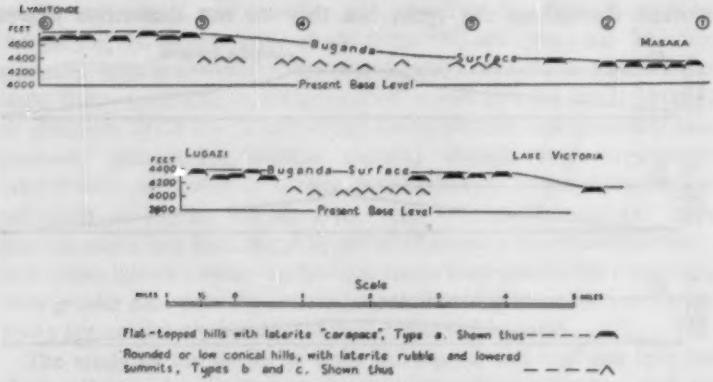
represent a former plane of erosion for, as G. K. Gilbert (1909) has pointed out : " the effect of an evenly spaced drainage network will produce, in homogeneous rocks, crestlines and hill-tops with accordant heights." In Buganda at least local regions with characteristic but differing summit heights do not indicate separate erosion cycles, but rather different stages in one erosion cycle. Physiographic divisions of Buganda can be based on the typical hill forms locally developed and representing one or other of the stages just described.

For the present argument it is significant to know the degree of summit lowering at the various stages. Unfortunately, only approximate estimations can be made on account of the lack of precise contouring. At present only form-lines at 50 feet and 100 feet have been drawn on the official geological map sheets, and additional scattered height determinations have been made by the author. As a rough

approximation, the average lowering of summits in this area may be considered to be 150 feet from Stage *a* to Stage *b*, and 200 feet from Stage *b* to Stage *c*. This presupposes an average altitude difference of about 500 feet between the higher erosion surface and base-level of the lower erosion surface. Slightly greater summit lowering may be characteristic where the base level of erosion is relatively lower.

The Recognition of Erosion Surfaces

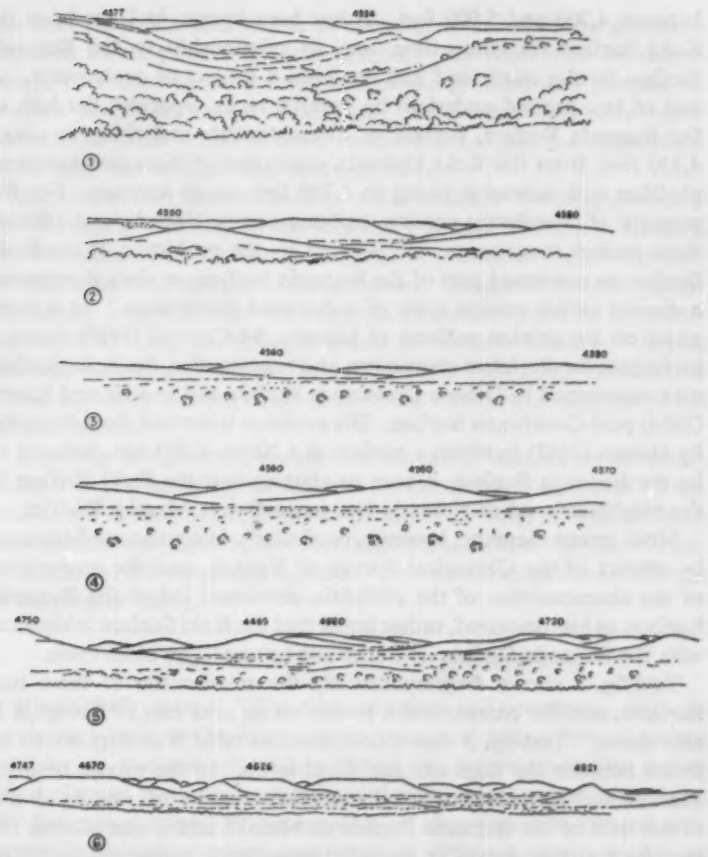
Over the greater part of Buganda two main erosion surfaces can be recognized. The Buganda Peneplain or Peneplain II (Wayland, 1920,



Text-fig. 2.—(*a*) Diagrammatic Profile approximately West-East across Masaka District. Numbers indicate positions of sketches of Text-fig. 3.

(*b*) Diagrammatic Profile approximately North-South from northern shore of Lake Victoria about 20 miles east of Kampala.

1933, 1934) is represented by the numerous flat-topped hills. Throughout most of Mmengo District and eastern Masaka this mid-Tertiary Surface is remarkably constant in altitude, varying only between 4,250 and 4,400 feet. The general stream pattern on this surface was probably little different from that of the present day. The lower erosion surface, or Peneplain III of Wayland, is immature, as stressed by the varying stages of evolution described in preceding paragraphs. Interference with its normal development has been caused by a fresh cycle of erosion inaugurated in Pleistocene times with consequent minor rejuvenation of the drainage caused by Rift valley faulting. Further complications were introduced by the changing levels of Lake Victoria, brought about by climatic oscillations. The base level of this lower erosion surface is about 3,800 to 3,900 feet over most of Buganda, but is some 200 feet lower in the northern part of the province.



TEXT-FIG. 3.—Field Sketches of Slope Forms in Masaka District, Uganda. (Heights indicated in feet).

(1) Buganda Erosion Surface ; looking south-west from Kiwala.

(2) Buganda Erosion Surface ; looking east from Mile 6, Masaka-Lyantonde road.

(3) Hills with lowered summits ; looking north from mile 19½, Masaka-Lyantonde road.

(4) Hills with lowered summits ; looking south from Mile 20½, Masaka-Lyantonde road.

(5) Transition zone with bevelled hills of the " Koki Surface " and hills with lowered summits ; looking south from Mile 33, Masaka-Lyantonde road.

(6) " Koki Surface " ; looking south-east from 2 miles west of Lyantonde.

In western Masaka a very striking group of flat-topped hills, separated by relatively deep valleys, displays a summit bevel which at first glance appears astonishingly flat, but on closer examination shows variation

between 4,700 and 5,000 feet. It has been known in Uganda as the Koki Surface for some time, and its relationship to the Buganda Surface further north and east has been a subject of controversy. A belt of low ground underlain by granitic rocks separates the hills of the Buganda Surface, formed of metasediments and rising to about 4,350 feet, from the Koki Uplands, composed of Karagwe-Ankolean phyllites and quartzites rising to 4,700 feet on an average. For the purpose of correlating erosion surfaces across Uganda and relating them to Rift movements, one is faced by the problem : is the Koki Surface an upwarped part of the Buganda Surface or does it represent a distinct earlier erosion cycle of widespread significance ? In a short paper on the erosion surfaces of Uganda, McConnell (1956) shows a preference for the latter alternative, and suggests that the Koki Surface may correspond to Dixey's Cretaceous Surface and to Fair and King's (1954) post-Gondwana Surface. His evidence is derived from mapping by Hatton (1952) in which a surface at 4,300 to 4,400 feet, believed to be the Buganda Surface, is seen to abut against the Koki Surface in the neighbourhood of Nakisaja Hill in northwest Masaka District.

More recent mapping, however, particularly in south-west Mmengo, by officers of the Geological Survey of Uganda, and the recognition of the characteristics of the pediplain developed below the Buganda Surface, as just described, rather imply that the Koki Surface is identical with the Buganda Surface and does not belong to an older cycle.

Text-fig. 2 shows diagrammatically the relationship of these two Surfaces, and for comparison a profile on an area east of Kampala is also drawn. Text-fig. 3 shows field sketches of hills as they are to be found between the Buganda and Koki levels. In the profile between Masaka and Lyantonde, the hills of types *b* and *c* of Text-fig. 1 rise to the level of the Buganda Surface at Masaka and if one accepts the premise that they represent degraded summits, it seems reasonable to assume that the erosion surface from which they were derived was some 200 to 250 feet higher, bringing it into coincidence with the Koki Surface. It seems probable, therefore, that we are dealing with one erosion surface warped as shown. The second profile demonstrates a state of affairs where no warping has occurred, except at the south end within the limits of Lake Victoria.

The hills of type *b* and *c* are identifiable, not simply by their shape, but by the characteristic lateritic rubble which is the last remnant of the older " duricrust ".

From the evidence of slope analysis it would appear that the Buganda Surface was upwarped a few miles west of Masaka. The amount involved is of the order of 300 feet over about twenty miles, an average slope of fifteen feet to a mile, or possibly greater over less distance. That there is no direct evidence of this warp may be explained by the

fact that the north-south zone of warping is underlain by granitoid rocks on which a relatively thin duricrust may have been developed which, combined with the readiness of the granites and gneisses to weather deeply in humid conditions, would allow for more rapid denudation. This would be quite comparable to what has taken place in the area east of Kampala described above.

Solomon (1939) drew attention to the evidence of tilting in south-east Ankole as provided by the formation of Lakes Nakivali, Kachira and Kijanebalola, a fact early recognized by Simmons and Wayland. At the same time Solomon also proposed, though with little precise supporting evidence, that the Buganda peneplain could be projected westward to form the hill-top bevels of western Masaka. Strong evidence for an upwarp of at least 200 feet between Lake Victoria and about 100 miles westwards is found in the Pleistocene deposits of the Kagera Valley.

A similar though smaller warp delimits Lake Victoria on its north-western shores, bringing the Buganda Surface down to 4,100 feet on the islands in the lake, as suggested on profile b, Text-fig. 2. The presence of quartzites and phyllites, however, has here assisted in the preservation of remnants of the Buganda Surface to provide the more direct evidence of warping or tilting.

Conclusions and Acknowledgments

King (1947) states : " The discrimination and correlation of cyclic landscapes rests in the first instance upon the recognition of planed surfaces . . . surfaces not widely planed but bearing a similar degree of relief may sometimes be correlated." The importance of recognizing the " *degree of relief* " by measurement of slopes must be stressed and, especially in regions where base-levels of different erosion cycles are separated by only moderate height intervals, their differentiation may be solely dependent on slope analysis. The broad outlines of erosional cycles in Africa have now been roughed out, but detailed mapping and local correlations must be increasingly dependent on observations of their slope elements.

The writer is much indebted to Dr. F. Dixey for critically reading the manuscript and offering useful suggestions. This paper is published by permission of the Director of the Geological Survey of Uganda.

REFERENCES

Cahen, L., and J. Lepersonne, 1952. Equivalence entre le Systeme du Kalahari du Congo Belge et les Kalahari Beds d'Afrique australe. *Mem. Soc. Belg. de Géologie.* Ser. 8, No. 4.

Dixey F., 1938. Some Observations on the Physiographical Development of Central and Southern Africa. *Trans. Geol. Soc. S.Af.*, xli, 113–172.

DIXEY, F., 1942. Erosion Cycles in Central and Southern Africa. *Trans. Geol. Soc. S.Af.*, xlv., 151–182.
—— 1944. The Geomorphology of Northern Rhodesia. *Trans. Geol. Soc. S.Af.*, xlvii, 9–45.
—— 1955. Some Aspects of the Geomorphology of Central and Southern Africa. Alex. du Toit Mem. Lect., *Geol. Soc. S.Af.*
—— 1956. Erosion Surfaces in Africa ; some considerations of Age and Origin. *Trans. Geol. Soc. S.Af.*, lviii, 265–280.
FAIR, T. J. D., and L. C. KING, 1954. Erosional Land-Surfaces in the Eastern Marginal Areas of South Africa. *Trans. Geol. Soc. S.Af.*, lvii, 19.
GILBERT, G. K., 1909. The Lowering of Hilltops. *Journ. Geol.*, xvii, 344–350.
HATTON, A. 1953. A report on the Geology of Map Sheet B-1-SW. *Unpub. Rept. Geol. Surv. Uganda.*
KING, L. C., 1947. Landscape Study in Southern Africa. *Proc. Geol. Soc. S. Africa*, l, pp. xxiii–lii.
—— 1951. *South African Scenery*, 2nd. Edition. Edinburgh.
—— 1953. Canons of Landscape Evolution. *Bull. Geol. Soc. Amer.*, lxiv, 721–752.
MABBUTT, J. A., 1955. Pediment Land Forms in Little Namaqualand, South Africa. *Geogr. J.*, cxxxi, 77–83.
MCCONNELL, R. B., 1956. The Erosion Surfaces of Uganda. *Col. Geol. Min. Res.* 5, No. 4, 425–428.
PALLISTER, J. W., 1954. Erosion Levels and Laterite in Buganda Province, Uganda. *C. R. XIX Int. Geol. Cong.*, fasc. 21, 193–199.
—— 1956. Slope Development in Buganda. *Geogr. J.*, cxxii, 80–87.
Premier Rapport de la Commission pour l'Etude des Versants, Union Geographique International, Amsterdam. 1956.
SOLOMON, J. D., 1939. In *The Prehistory of Uganda Protectorate*, T. P. O'Brien, Cambridge.
WAYLAND, E. J., 1920. *Ann. Rept. Geol. Surv. Uganda*, p. 15
—— 1933. The Peneplains of East Africa. *Geogr. J.*, lxxxii, 45.
—— 1934. Ann. Rept. and Bul. No. 1., *Geol. Surv. Uganda*, 77–79.

GEOLOGICAL SURVEY,
ENTEBBE,
UGANDA.

Contact Phenomena from N.W. Jersey, C.I.

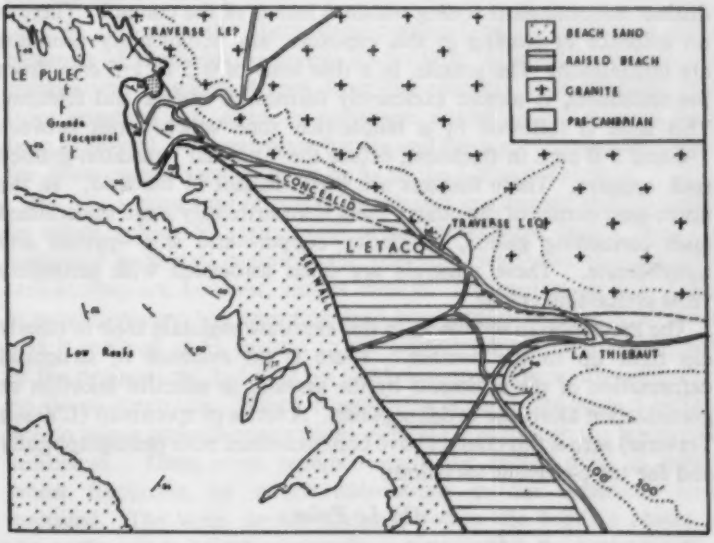
By F. A. Henson

Abstract

The field relationships between the Armorican granite of North-West Jersey and the Precambrian sediments in the Le Pulec and L'Etacq areas are described together with the petrography of the contact rocks. Trace-element determinations on rocks from two traverses across contacts in the area, and upon control specimens of granite and sediments supplement the petrography. The mechanism of granite emplacement in this area is discussed.

Introduction

In North-West Jersey, from Le Pulec to L'Etacq, intricate contact phenomena between a medium-grained biotite-hornblende granite and Precambrian sediments are magnificently exposed in the off-shore reefs and coastal sections. The area is shown in Text-fig. 1. The contact phenomena were first discussed by Plymen (1921) and later by Groves (1930). In 1931 Wells and Wooldridge (1931) critically discussed the earlier works. The contact phenomena have recently been re-examined and the petrography of the granites and hornfelsed



Text-fig. 1.—Geological sketch map of the L'Etacq area showing the distribution of granite and Precambrian sediments. The positions of the two traverses across the contacts at Le Pulec and at L'Etacq are also shown.

Precambrian sediments is supplemented by trace-element determinations.[1]

In the area under consideration the Precambrian sediments, which are predominantly of the greywacke suite, have a regional dip to the north-east between 40 and 60 degrees. Locally the sediments are folded into complex anticlinal and synclinal structures, as in the reefs south of L'Etacq. The sediments, which are characteristically grey-green mudstones and siltstones, frequently show current-bedding and minor variations in texture. Near to the granite they are usually altered to purple hornfelses, in which the original banding becomes more pronounced. These harder indurated sediments form the feature known as Grande Etacquerel, and the smaller mass west of Le Pulec.

Field Relations

(*a*) *L'Etacq Quarry*

The simplest contact in the area is that exposed on the western face of the recently-worked L'Etacq quarry. Here the Precambrian sediments dip to the north at angles varying from 60 to 65 degrees, whilst the plane of the granite-sedimentary contact is inclined to the south at 60 degrees. This granite, a medium-grained biotite-hornblende granite very similar to that of South-West Jersey, is characterized by distinct mineralogical zoning within 6 inches of the contact. There is no evidence of stoping in this exposure, and sedimentary xenoliths are uncommon. The granite, in a thin zone of 0·5 to 1·5 cms. from the sediments, is almost exclusively formed of quartz and feldspar. This zone is followed by a biotite-rich zone which varies between 1·0 and 3·0 cms. in thickness, before the " normal " medium-grained rock appears. These features are quite distinct in the field. In the north-west corner of the quarry there is an extremely small mineralized fault containing galena, sphalerite, copper—and iron—pyrites and molybdenite. These minerals are often associated with secondary veins containing calcite.

The Precambrian sediments in this exposure maintain their northerly dip right up to the contact. There is no evidence of structural deformation of the sediments by the granite, or selective injection or granitization along the bedding planes. A series of specimens (L'Etacq Traverse) across this contact have been examined both petrographically and for trace-element variations.

(*b*) *Le Pulec*

In this area the Precambrian sediments dip to the north-east at angles from 40 to 60 degrees. They are well-bedded grey-green mudstones and siltstones identical with those in the L'Etacq quarry and the extensive reefs to the south. The sediments usually maintain

their well-bedded character right up to the contact, which is oriented from north-west to south-east. In a few areas the sediments have been distorted and crumpled, and in the extreme case micro-brecciation and mass injection of quartz veinlets has occurred.

At Le Pulec the granite is identical with that of L'Etacq. Aplo-granite veins, however, are more numerous and distinct. Quartz veins, varying in thickness from 1 to 3 inches, also occur. They have a general easterly " dip " of 25 to 30 degrees and are later than the aplites.

A small mineralized fault zone, oriented from north-west to south-east, and in contact with both hornfelsed sediments and granite, also occurs at Le Pulec. Sphalerite and galena occur in the mineralized fault breccia, which at its maximum development is only 3 feet wide. A description of this feature and its relationship to the sediments, the granites, and mica-lamprophyres will be published later.

At Le Pulec the sinuous contact between the Precambrian sediments and the biotite-hornblende granite is exposed for a distance of more than 250 yards. Over this comparatively short distance the nature of the contact varies considerably. Four types of contact phenomena are recognized, viz.: (i) sharp cross-cutting contact (L'Etacq type); (ii) stoped contact; (iii) contaminated contact; (iv) granitic veins in the sediments.

(i) In this area the sharp cross-cutting type of contact is quite common. Essentially the granite shows little variation in texture and composition to within 4 cms. from the contact; it is relatively free from xenoliths. A series of specimens across such a contact have been examined, both petrographically and for trace-element variation, for direct comparison with the rocks of the L'Etacq Traverse.

(ii) The second type of contact is exposed in a rugged cliff, dissected by minor gullies, 50 yards north of the mineralized fault. Here the indurated sediments maintain the regional north-west to south-east strike; they are, however, almost vertical. The contact surface, which is roughly planar, has been examined over a total distance of 20 yards and is inclined at 55 degrees to the south-west on the northern side of the promontory, but changes to 85 degrees to the south-south-west on the southern side. Minor irregularities occur in the contact surface due to minor upward penetrations of granitic veins into the hornfelsed sediments. These veins generally leave the parent mass at points where fracturing, or minor dislocations in the sediments have occurred. The veins do not normally follow the bedding planes in the sediments. Micro-veining by quartz, which in some cases s clearly related to the granitic veins, is common.

At its contact with the sediments the granite is fine-grained and flinty in appearance. This fine-grained zone rarely exceeds an inch

in thickness. A similar fine-grained rock also surrounds the sub-angular xenoliths, these rarely exceed 9 inches in diameter. The margins of these sub-angular xenoliths are sharp and clearly defined on their upper surfaces close to the contact, but their under surfaces are diffuse and ragged. Their centres are usually veined by quartz. In some cases, at 12 to 15 inches from the contact surface, the xenoliths have been feldspathized and have completely lost their sedimentary structures. Below the feldspathized xenoliths are thin and irregular biotite-rich bands, rarely exceeding an inch in thickness and characterized by very diffuse margins. These bands are interpreted as being the remnants of earlier and partially digested xenoliths. In other parts of the granite diffuse patches of biotite-rich rock also occur; these rarely exceed a few square inches in area. Small patches of pegmatitic quartz and feldspar also occur within the xenolith zone; they are, however, uncommon. At a distance of 5 feet from the contact surface the granite is uniformly medium-grained and comparatively free from sedimentary xenoliths.

(iii) In this type of contact the granite, at a variable distance of 3 to 8 feet from the sediments, is contaminated by both sub-angular sedimentary xenoliths and diffuse biotite-rich bands. The former rarely exceed 9 inches in length; the latter cannot be traced for more than a few inches. Quartz and feldspar pegmatitic veins also occur. The essential difference between the contaminated contacts and the stoped contacts is that in the latter type mechanical deformation and the injection of granitic material have predominated over the processes of feldspathization and granitization. In the contaminated type of contact mechanical deformation and injection of granitic materials appear to play subordinate roles.

In the field the marginal contaminated granite occurs as large offshoots from the main granite body. Such contaminated rocks are variable, both in texture and composition. Their brecciform appearance suggests that they were formed as the result of injection and accompanying granitization. In comparison with the biotite-hornblende granite the marginal variety is finer-grained, darker in colour, and contains porphyroblastic quartz and feldspars. In parts the marginal granite is also rich in biotite. The best example of a contaminated contact is to be seen in the granite tongue into the Precambrian, some 50 yards north of the slipway at Le Pulec. This tongue is orientated from south-east to north-west, parallel to the strike of the sediments.

(iv) Many of the granitic veins, which occur in the reefs and cliffs at Le Pulec, can be traced to their parent granite in the eastern cliff. Those which occur further west are either major feeders several feet in width, or offshoots from such larger masses. Near to the granite

the veins almost invariably cut across the bedding planes of the sediments, although parts of the margins of such veins may follow bedding planes for short distances. Further away from the granite the veins, which are identical with those east of Le Pulec, generally follow the bedding planes.

In the cliffs north-east of the slipway at Le Pulec a large composite granitic vein can be traced southwards for nearly 25 yards from its parent granite mass. This vein, at its junction with the granite, varies in thickness between 15 and 18 inches. It is a fine-grained granite with abundant biotite. An offshoot cuts the bedding planes of the indurated Precambrian at 60 to 80 degrees. At 8 feet from its source the vein becomes composite in character, it shows distinct zoning with three or four biotite-rich bands of 0·5 to 2·0 cm. in thickness in its upper part; a coarse-grained centre and clear-cut margins. The composite character of this vein is extremely variable laterally.

At 30 feet the vein splits and exhibits many interesting features. It is formed of three distinct parts, viz.: upper and lower fine-grained granitic veins with sharply-defined outer margins and a darker central part, in which porphyritic quartz and feldspar are abundant. The inner margins of the granitic veins, which are th mselves variable in character, are less clearly defined than the outer margins. Evidence of the intrusive character of the granite veins is afforded by local micro-brecciation of the sediments and the partial contamination of the upper parts of the veins by sediments.

Even further away from the parent mass the granitic veins decrease to 2 or 3 inches in thickness; they are still variable in character. Their margins are quite distinct; the upper part, in contact with the sediments, is predominantly quartz and feldspar rich. Below this flakes of biotite are common (these do not show flow-orientation) whilst the central part is often pegmatitic. The occurrence of large biotite flakes seems to be related to the development of pegmatitic centres.

Similar composite veins are commonly developed in the reefs north of Grande Etacquerel. In some of these veins brecciated zones occur. In others the development of pegmatitic centres, with masses of quartz several inches thick in their central parts, has taken place. Several large veins, with pegmatitic centres, occur within the sediments north of the mineralized fault breccia.

Petrography of the Contact Rocks

(i) *L'Etacq Quarry*

The rocks of this traverse, from a medium-grained granite to the Precambrian sediments, are all from the western face of the quarry.

The line of traverse is from north-north-east to south-south-west; all specimens were taken on the same horizontal line.

DETAILS

Specimen Number.	*Rock.*	*Distance from the Contact.*
1	Granite	8 feet
2	,,	4 feet
3	,,	2 feet
4	,,	12 feet
5	,,	6 feet
6	,,	3 to 1 inches
7	,,	1 to ½ inch
8	,,	½ to 0 inch
9	Sediment	0 to ½ inch
10	,,	½ to 2 inches
11	,,	2 to 4 inches
12	,,	4 to 6 inches
13	,,	9 inches
14	,,	15 inches
15	,,	2 feet
16	,,	3 feet
17	,,	5 feet
18	,,	8 feet

The granite on the traverse shows interesting variations in composition and texture. The essential constituents are quartz, perthite, plagioclase (An_{18}–An_{14}), biotite with sporadic hornblende and accessory minerals. Rosiwal analyses show that perthite increases in amount in the contact zone where it forms 50 per cent of the rock; there is a complementary decrease in the amount of plagioclase to 5 per cent. Biotite and the iron ores show a pronounced maximum at half an inch from the contact. Quartz, which is remarkably constant throughout the traverse, usually shows serrated edges and frequently occurs as corroded relics within the feldspars. Two generations of perthite have been recognized and within the contact zone intergrowths of quartz and perthite are common. The plagioclase feldspar is invariably partly sericitized; it often contains numerous inclusions. Within 12 inches of the contact there is a general decrease in the grain-size of all constituents (except biotite); an increase in the abundance of corroded and optically continuous quartz relics both in the feldspars and the groundmass, together with an increase in the number of inclusions of earlier plagioclase and perthite relics within each other.

The sediments, at their contact with the granite, have been altered to a biotite hornfels. Microscopically this rock exhibits a glomeroporphyritic texture, due to the formation of diffuse patches of quartz and feldspar. Three inches from the contact the hornfels becomes biotite rich; this mineral forms between 60 and 70 per cent of the rock and occurs as small flakes showing a common orientation. Two inches further away from the contact biotite gives way to hornblende;

this mineral occurs as extremely small granular and irregular crystals. It is strongly pleochroic and is associated with quartz, chlorite, sericite, magnetite, hæmatite, apatite, and occasional large composite quartz crystals. Both cordierite and spinel occur but these minerals are comparatively rare.

Beyond the hornblende hornfels, which is a thin band less than an inch in thickness and roughly parallel to the contact plane, the sediments are less altered. The textures are variable and probably reflect variations in the original banding. Traces of bedding are preserved at 5 feet from the contact; at 8 feet the sediments are almost unaltered. The amount of iron ore, however, is much higher than that found in unaltered sediments, it forms between 10 and 15 per cent of the rock which is slightly spotted due to small patches rich in chlorite and sericite.

(ii) *Le Pulec Traverse*

This traverse was taken across an intrusive contact, similar to that of L'Etacq quarry, for the purpose of comparing trace-element variations. In this traverse the specimens, however, were taken along a bedding plane and should, therefore, indicate changes due to the emplacement of the granite upon sediments of fairly uniform character.

Specimen Number.	Details. Rock.	Distance from Contact.
1	Granite	4 feet
2	,,	3 feet
3	,,	2 feet
4	,,	12 inches
5	,,	2 to ½ inches
6	,,	½ to 0 inch
7	Sediment	0 to ½ inch
8	,,	12 inches
9	,,	2 feet
10	,,	3 feet

Microscopically the granite exhibits many of the textural variations described in the previous series. One notable exception, however, is the magnificent runic textures which occur in the quartz-rich contact. The sediments are biotite-hornfelses; their mineral assemblages and textures are similar to those of the detailed traverse. There is no development of a hornblende-hornfels in this traverse.

(iii) *Contaminated Granite*

Macroscopically this marginal granite is a fine-grained pale grey rock, in which both small patches and diffuse biotite-rich bands occur. The texture and mineralogical composition are extremely variable. Microscopically this granite differs from those described above; firstly, by the presence of abundant clastic quartz, which occurs chiefly

in small irregular patches and as unorientated relics within the feldspars (predominantly in perthite); secondly, by micro-faulting and the deformation of biotite and the albite lamellæ in plagioclase, and thirdly, in the absence of micrographic intergrowths. As in L'Etacq and Le Pulec traverses both types of feldspars occur as inclusions within the larger and frequently serrated quartz. Where biotite is abundant it occurs as unorientated flakes associated with the iron ores and the accessories. Many of the minute flakes are chloritized and commonly occur as inclusions within the feldspars, or at the margins of the larger serrated quartz.

Trace Elements

The specimens from which sections were cut in the L'Etacq and Le Pulec traverses were also used for trace element determinations [1] across these two contacts. Values obtained are given in Table 1, together with values of trace element determinations for ten other specimens taken as controls. The specimens 1 to 5 were taken at 2-ft. intervals across the bedding in a small quarry at the foot of Jubilee Hill, St. Peter's. This quarry is approximately half-way between the granite masses of North-West and South-West Jersey; the specimens are, therefore, assumed to be unaltered by the emplacement of either of these masses. Specimens 6 to 10 used as controls for the granite were taken at 2-ft. intervals on the back wall of the granite quarry north of La Thiebaut, L'Etacq. This wall is approximately 100 yards north of the granite-sedimentary contact.

In the L'Etacq traverse the most significant feature revealed by these values is that the sediments are richer, both in the number and the relative amounts of trace-elements, than granite. The only exceptions being the elements Mo and Be which are present only in the granite in amounts approximate to their sensitivity, they are found only within the sediments at 1 inch from the contact. The elements Sc, Co, and Ni do not occur within the granite in this traverse, whilst Pb and V are restricted to a narrow zone within an inch of the contact. In the Le Pulec traverse the values of trace-elements show the same general pattern. Cr shows an interesting distribution in the L'Etacq traverse. With the exception of specimen 8 it is absent from the granite, yet the adjacent specimen in the sediments contains over twenty times the amount contained within the granite. Further, the maxima for Cr on the traverse occurs in specimens 16 and 17 some distance from the contact and in amounts considerably in excess of those found in the controls. Sn is present in appreciable amounts in both sediments and granite. There are four maxima for

[1] Values obtained in the Department of Mineralogy and Petrology, Cambridge, by kind permission of Professor C. E. Tilley, F.R.S.

TABLE 1

	ELEMENT	La	Cr	Sc	Co	Zr	Ni	Y	V	Mo	Sn	Pb	Be	Cs	Rb	Li	Sr	Ba	Ga
	SENSITIVITY	20	1	15	5	10	5	10	5	2	10	10	5	10	5	1	5	5	2
L'ETACQ QUARRY TRAVERSE	1	-	-	-	-	100	-	30	-	3	20	-	5	-	150	7	10	220	10
	2	20	-	-	-	125	-	30	-	3	40	-	8	-	320	7	25	220	10
	3	20	-	-	-	125	-	20	-	3	40	-	5	-	320	5	5	320	10
	4	45	-	-	-	80	-	25	-	2	40	-	8	-	150	7	5	320	10
	5	45	-	-	-	125	-	20	-	5	40	-	8	-	200	5	5	320	10
	6	-	-	-	-	50	-	10	-	2	30	-	5	-	450	10	10	400	7
	7	35	-	-	-	65	-	25	-	3	50	20	5	-	320	5	7	400	10
	8	45	5	-	-	125	-	20	20	3	40	10	5	-	450	15	100	400	10
	9	100	100	30	10	125	25	45	100	10	20	20	8	-	600	45	300	600	15
	10	-	55	20	12	125	30	20	100	5	70	20	-	-	320	55	300	1000	12
	11	-	70	15	10	80	40	15	100	-	70	10	-	-	450	45	300	600	10
	12	-	70	15	12	125	40	25	100	-	40	10	-	-	180	55	300	200	10
	13	-	55	15	12	125	40	20	100	5	50	20	-	-	320	45	220	1000	12
	14	-	55	20	12	125	40	20	100	5	70	20	-	-	180	45	300	1000	10
	15	-	55	20	12	100	40	20	100	-	25	10	-	-	180	55	300	1000	10
	16	45	150	20	15	125	40	20	100	-	50	15	-	-	320	90	120	700	10
	17	45	150	25	15	125	40	20	100	-	100	20	-	-	250	70	180	700	10
	18	45	55	20	10	125	20	20	100	-	50	-	-	-	150	20	35	600	10
LE PULEC TRAVERSE	1	-	-	-	-	125	-	20	-	10	-	70	2	-	100	7	25	400	10
	2	-	-	-	-	80	-	20	-	2	-	15	5	-	200	5	15	220	10
	3	-	-	-	-	65	-	15	5	2	-	10	5	-	200	5	30	320	10
	4	45	-	-	-	350	5	30	-	2	25	15	8	-	200	10	25	700	10
	5	35	-	-	-	125	-	20	-	2	25	10	8	-	200	7	35	220	12
	6	-	2	-	-	40	-	10	-	-	20	-	2	-	320	5	15	220	7
	7	45	30	-	5	125	20	20	45	2	50	30	-	-	140	45	100	400	10
	8	70	55	15	10	350	20	20	55	2	25	15	-	-	70	55	180	500	10
	9	-	100	15	10	550	20	20	55	-	20	-	-	-	100	70	180	400	10
	10	45	55	15	10	350	25	20	70	-	20	-	-	-	100	90	120	220	10
SEDIMENTS	1	-	45	10	5	100	40	15	85	-	20	20	-	-	175	45	400	1000	15
	2	-	45	10	15	180	40	15	85	-	-	15	-	-	200	45	320	1000	15
	3	-	45	10	5	150	40	15	85	-	-	20	-	-	175	45	400	1000	15
	4	-	60	10	10	100	40	15	100	-	-	15	-	-	200	65	320	1000	20
	5	-	45	10	10	250	40	15	85	-	-	20	-	-	175	45	400	1000	15
GRANITE	6	-	3	-	-	100	8	30	5	-	-	10	-	-	400	35	50	300	15
	7	-	-	-	-	100	5	20	-	-	-	10	-	-	400	35	50	350	10
	8	-	-	-	-	85	5	20	-	-	-	10	-	-	400	30	50	300	15
	9	-	-	-	-	100	5	30	-	-	-	10	-	-	400	45	50	300	15
	10	-	-	-	-	100	5	30	5	-	-	10	-	-	400	45	50	300	10

this element on the traverse. These clearly-defined rises and falls suggest a rhythmic occurrence of this element in the traverse.

Li is only present in 5 to 15 p.p.m. in the granite, but increases to a maxima of 90 p.p.m. in the sediments (specimen 16) at a distance of 3 feet from the granite contact. Again, there is a rhythmic variation in the occurrence of this element, although it is not so clearly defined as in the case of Sn. However, for both Sn and Li the most pronounced rise and fall occurs in the sediments at distances of 5 feet and 3 feet

from the contact. Sn, with its slightly smaller ionic radius, achieves its maxima at a greater distance from the contact than Li.

In the case of Pb, which can only be determined to 10 p.p.m., the variations from 10 to 20 p.p.m. cannot be interpreted as showing rhythmic variations of the kind indicated by Sn and Li. Zr, on the other hand, is the most uniformly distributed trace-element in the traverse. It is present in both the granite and the sediments in amounts ranging from 50 to 125 p.p.m. The lowest value of 50 p.p.m. (granite, specimen 6, at 12 inches from the contact) is followed by successive values of 65 and 125 p.p.m. across the contact. There is no justification for interpreting the values for Zr, in specimens 6 to 11, as a significant rise and fall of the kind encountered in the elements of Sn and Li. The granite in specimen 6, and the sediments in specimens 11 and 15, are merely deficient in Zr when compared with the remainder of the traverse. Y is the only element in the traverse which is more common in the granite than in the sediments. Two distinct maxima for Y, at the contact and at 6 inches from the contact, occur in the sediments.

Sr, Ba, and Rb are present in amounts greatly in excess of the elements previously described. Sr is only present in small amounts in the granite, except at the contact where it rises abruptly from an average 10 to 100 p.p.m. With the exception of a slight decrease to 220 p.p.m. in specimen 13, all the sediments from the contact to a point 3 feet away from it, contain over 300 p.p.m. of Sr. Beyond this point the amounts of Sr decrease to a value of 35 p.p.m. The values for Ba on the traverse show a progressive rise from the beginning of the traverse to a maxima, in the sediments, at 1 inch from the contact. A second Ba rich series occur between 9 and 24 inches from the contact, after which the values for Ba fall. Although the values for Rb on this traverse are very irregular it is possible to indicate at least two rhythmic variations. The first in granite rises to a maximum of 450 p.p.m. in specimen 6 at 2 inches from the contact. The second, which is also the maximum for the traverse, occurs in specimen 9 in sediments at the contact. Strict comparisons cannot be made between the two traverses; some very marked similarities do, however, occur. In both traverses the elements Cr, Sr, Ba, and Rb show the same pattern in their distribution and in the amounts in which they are present. Other elements show wider variations, but all follow the same general pattern in each traverse.

Conclusions

In this area the contact phenomena, and consequently the rocks within the contact zone, are extremely varied. The biotite-hornblende granite closely resembles that of South-West Jersey (Henson, 1947)

and may also be considered as a high level and younger member of the Hercynian granite series. Although the Precambrian sediments are extensively folded there is little evidence of their regional disturbance due to the emplacement of the granite. Micro-tectonics, which can be directly attributed to the granite, are, like the indurated sediments, restricted to a narrow peripheral zone.

The various contact phenomena in this area are interpreted as being almost entirely due to the effects of such minor tectonics in the peripheral zone. The development of large fractures would be accompanied by the injection of granitic material to give the composite veins described. The irregular blocks of sediments found in such veins support this view. It is suggested that local granitization would accompany injection. It is also likely that micro-faulting and fracturing of the sediments, which might have reached the stage of hornfelses at this stage, materially assisted both stoping and consequent assimilation. Micro-veining by quartz is another manifestation of the same process, but on a much smaller scale.

There is no field evidence to support the view that this granite was wholly emplaced by a process of granitization. There are local " basic " bands, both within the marginal granites and the sediments. Such bands are thin and irregular; they are interpreted as representing local phases of basification of the country rock *in situ*. The occurrence of the biotite rich zone, together with the fine-grained quartz-feldspar margin exhibiting replacement textures in the L'Etacq traverse, may indicate some outward movement of the contact zone during replacement. The mineralogical and textural changes in this, and other traverses, suggests that where the effects of basification, feldspathization, and silification are observed then the processes of granitization have clearly operated. There is no evidence, however, which conclusively indicates that these processes have been the sole mechanism of emplacement. It is proposed that in this area they accompanied magmatic injection.

Trace-element determinations in the control series and the two traverses across granite-sedimentary contacts reveal significant features in their distribution. The values obtained in the controls are remarkably uniform and emphasize the considerable variations across the contacts. In both traverses nearly all elements are present in amounts many times greater than the sensitivity of the method used in their determination. Furthermore, nearly all elements are present in amounts in excess of those obtained in the control series. There is marked agreement in the distribution of the trace-elements in these two traverses which is most significant, since the L'Etacq series were taken down the dip of the hornfelsed sediments whilst those in the Le Pulec traverse were taken from one bedding plane. Both these

facts, and the greater variety and amounts of trace-elements in the sediments of the contact zones, clearly suggest that some transfer of matter from the granite to the sediments occurred during the period of emplacement. How this was achieved is a matter of conjecture, but these determinations also show that there is some relationship between the ionic radius of the element and the position of its maxima on the traverse. The elements Cr and Sn, with ionic radii of 0·65 and 0·74, attain their maximum in specimens 16 and 17 on the L'Etacq traverse, whilst Rb (I.R. 1·49) attains its maximum on the same traverse at specimen 9. The same elements show very similar distribution in the Le Pulec traverse. The values obtained indicated that there may be more than one maxima for an element across a contact and that dispersion may follow the same rhythmic variation as observed mineralogically in the granites of South-West Jersey.

In conclusion, the author would like to express his thanks to his colleagues Dr. R. B. Elliott and Dr. R. J. Firman for discussion of these rocks in the field; to Dr. S. R. Nockolds for checking the trace-element determinations, and to Professor W. D. Evans for his assistance in this work and his encouragement of the author's researches in the Channel Islands.

REFERENCES

GROVES, A. W., 1930. The Heavy Mineral Suites and Correlation of the Granites of Northern Brittany, the Channel Islands and the Cotentin. *Geol. Mag.*, lxvii, 218–240.

HENSON, F. A., 1947. The Granites of South-West Jersey. *Geol. Mag.*, lxxxiv, 273–280.

PLYMEN, G. H., 1921. The Geology of Jersey. *Proc. Geol. Assoc.*, xxxii, 1951, 172.

WELLS, A. K., and S. W. WOOLDRIDGE, 1931. The Rock Groups of Jersey, with special reference to Intrusive Phenomena at Ronez. *Proc. Geol. Assoc.*, xlii, 178–215.

DEPARTMENT OF GEOLOGY,
THE UNIVERSITY,
NOTTINGHAM.

The Terrace Sequence at Dale-I-Sunnfjord

By Alice Coleman

Abstract

A series of terraces in the Dale Valley south of Dalsfjord has been mapped, and heights have been established. The results have been analysed into a sequence of stages, and compared with general conclusions advanced by J. Rekstad and F. Nansen, on the isostatic displacement of postglacial terraces in Norway.

THE post-glacial uplift of parts of Scandinavia has initiated a series of terraces which attract the geomorphologist by their remarkably distinct sculpture as individual land-forms and at the same time create problems by their distortions of level when traced over any considerable distance. Norwegian workers such as F. Nansen, J. Rekstad, and others have overcome the difficulty of long-distance correlation and provided a general denudation chronology. The present investigation contributes the local sequence of the Dale valley (latitude 61° 22′ N., longitude 5° 22′ E.) as detail to a larger picture.

The increase of isostatic recovery inland towards the area of former maximum depression under the ice load was traced by Rekstad by means of the upper limit of post-glacial marine submergence and clay deposition. This limit is marked by a conspicuous terrace. It is succeeded below by features denoting a stepped emergence interrupted at one point by renewed marine submergence. This latter is capable of correlation by marine mollusca, including *Tapes virginea* which gives the corresponding terrace its name. Thus both the Main Terrace at the upper marine limit and the Tapes Terrace possess diagnostic characters which enable them to be traced and correlated over wide areas. Naturally the two diverge vertically from each other when traced inland, but Nansen has shown that their relative spacing can be expressed by the formula

$$h - H \times 0{\cdot}315 + 3{\cdot}4 \quad \text{(1921, p. 260)}$$

where h and H are the heights in metres of the Tapes Terrace and the upper marine limit respectively.

The observations at Dale were all taken at or below the upper marine limit which here lies at about 45 metres, and as far upstream as the Dale Falls. Further up the valley, and also above the 45-metre contour at its lower end, the topography is glacially roughened down to the upper marine limit which is marked by a sharp discontinuity. Below it are the fresh and sharply chiselled terraces and benches which have obviously never been overridden by ice. It is possible to see at a glance the morphological transition from the Ice Age to post-glacial time in the 45-metre contour.

Field observations included careful mapping of the flat tops of the

terraces and the establishment of spot heights by means of precise levelling and aneroid survey. In all eighty-three flats were mapped, and height information obtained for seventy-five of them (Text-fig. 1). Morphological analysis was carried out by means of this map used in conjunction with the height range diagram (Text-fig. 2), in which the heights of the flats have been plotted against their distance up-valley from a point off the mouth of the Dale Elv. The map and diagram reveal five stages of downcutting:—

(*a*) An upper marine stage at about 45 metres (the Main Terrace);
(*b*) A stage of rapid downcutting with few terraces;
(*c*) A river terrace grading down to 11 metres;
(*d*) A bench at 5 to 7 metres;
(*e*) A continuous series of flood plain stages at every level between (*d*) and the fjord.

This sequence of events and the supporting evidence will now be discussed in greater detail.

At the retreat of the ice and the valley below the falls was left irregularly scoured, and in part deeper than at present, as testified by the stratified outwash material occurring at 12 metres near Steia. This was next invaded by the sea to the 45 metre level, and infilled with a marine clay, some of which is exposed near Yksnebjör. This sea also acted as a base level for the planation of the valley to a width of about half a mile, across both solid rock and morainic material alike. The planed surface has since been dissected to form the highest and largest terrace of the area, namely (*a*), the Main Terrace. It stands out most conspicuously in the field, since it is backed by true mountain slopes and fronted by deep bluffs with a considerable interval to the next stage below. It extends upstream at a constant altitude to within 300 yards of the Dale Falls. This constancy suggests that the feature is marine in origin, a conclusion supported by its reappearance at exactly the same elevation in the little Yksnebjör valley where a riverine feature would certainly show a steep rise. Consequently, the lower Dale valley at the 45 metre period can be regarded as an inlet of the Dalsfjord similar to many which exist to-day.

The well-preserved form of the surface also proves that there has been no significant warping *within* the area during the post-glacial uplift. We can therefore regard the lower surfaces also as free from tectonic distortion on any appreciable scale.

(*b*) The Main Terrace was succeeded by a phase of accelerated downcutting which allowed little scope for lateral planation, until below about 25 metres—the actual height rises upstream—where numerous terraces are crowded together within so small a vertical range that the task of distinguishing separate stages is very difficult.

It is perhaps permissible to claim a terrace stage grading down to about 15 metres, but the more cautious view adopted here ascribes these features to the final, slackening phases of downcutting before a still-stand at 11 metres. Clearly this was a period when the effects of still-stand were inoperative while those of isostatic uplift and falling sea-level were dominant.

(*c*) An 11 metre terrace can be traced upstream with a gradual rise at an increasing rate, to over 20 metres. This provides a typical riverine profile, but at the same time planation was restricted and never extended so far upstream as that of the Main Terrace.

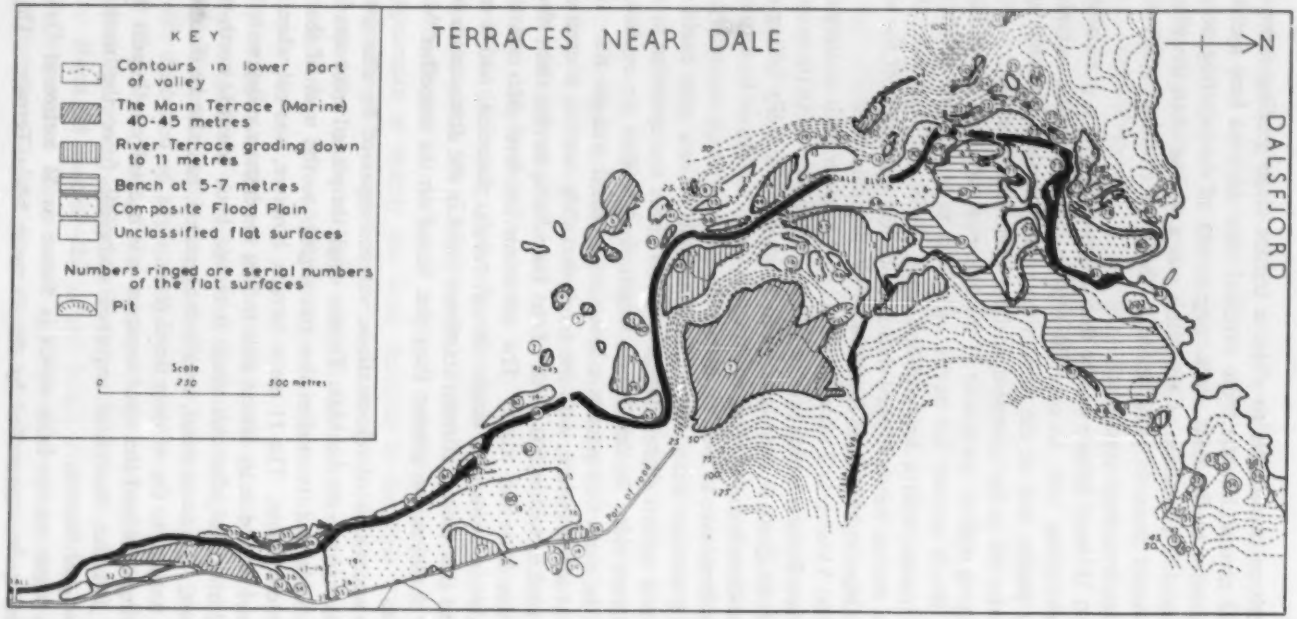
(*d*) Lying slightly north-west of the 11 metre surface is a very large feature which extends for half a mile at a very constant height of 5 to 7 metres, with a low cliff-like back. It is not impossible that this is a marine bench formed during a shallow ingression of the sea, but no deposits have been found in supporting evidence.

(*e*) The 5 metre to 7 metre bench is at the upper limit of irregular flood plain features which exist at minute intervals down to the present level of the fjord. There is no need to invoke a steadily falling sea level for these features: they could equally well be formed by a stream shifting from side to side as it cuts slowly down to a stationary or nearly stationary limit. In such circumstances new cuts could be juxtaposed against slightly higher ones on either the upstream or the downstream side. In detail their longitudinal profiles are confusing, but in the mass they possess a lower longitudinal gradient than that of the 11 metre terrace, with the result that they overrun it upstream and extend to within 500 yards of the Dale Falls, having risen about 20 metres from the coast. The numerous low-level flats are thus explicable in terms of a single, though rough, planation, and it may be noted that their maximum transverse relief in the downstream part is only 5 metres, no greater than that found on the smoother Main Terrace.

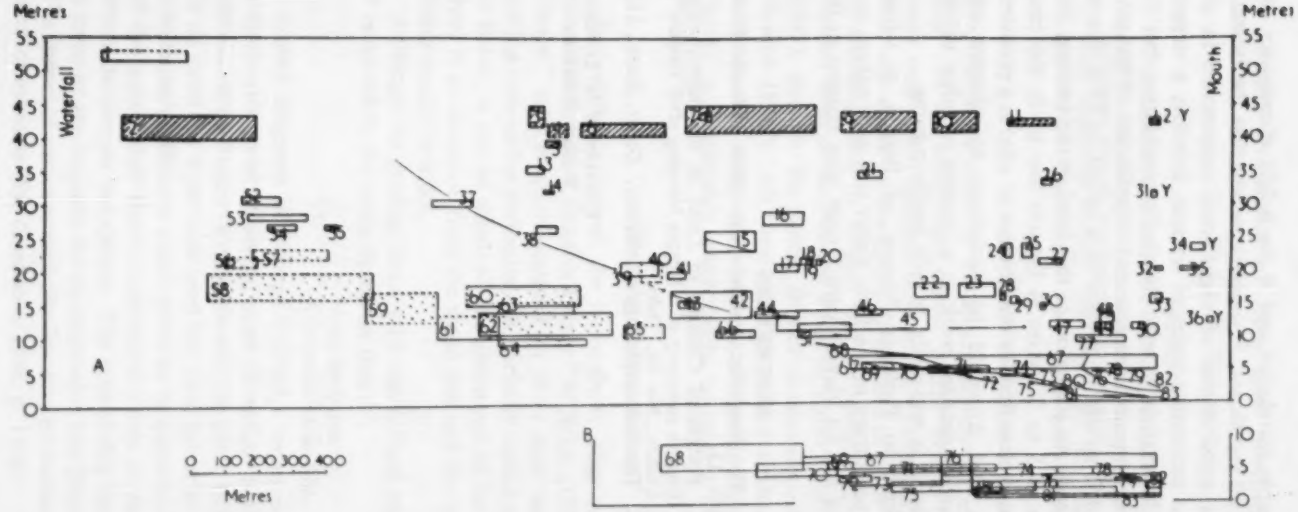
This succession of rejuvenations was accompanied by changes in the valley plan. At the Main Terrace stage the planed tract was half a mile wide and its median line ran slightly to the west of that of the present valley. The 11 metre terrace, however, was cut when the river had moved in its lowest mile to hug the eastern valley wall, but both during and after this phase it moved back towards north-west and west. The same trend, locally exaggerated, can also be discerned in the passage to the modern flood plain.

Having examined the local sequence it is necessary to inquire how far it fits the theoretical sequence deducible from the work of Rekstad and Nansen.

The upper marine limit which is shown as 51 metres at Dale is believed to be represented by the 45 metre Main Terrace. This is



TEXT-FIG. 1.—Postglacial terraces at Dale.



TEXT-FIG. 2.—Height range diagram to show stages in terrace formation. Each rectangle represents one terrace flat, its base being proportional to the north–south extent and its side to the height range of the flat. The sloping lines within the rectangles are gradient lines, representing as near as may be the ancient thalweg. The main terrace fragments are shaded and those of flood plain stippled. The large meander at the mouth crowds the symbols and distorts the gradient lines if only simple southward measurements are used as in A, and the northern flood plain flats are set out again below in B, with distances from the mouth measured along the river's course.

Flats marked Y are situated in the Yksnebjör tributary valley.

a perfectly reasonable correlation and if the height discrepancy can be regarded as at all significant, it suggests merely that the isostatic uplift has suffered some degree of slight local suppression in the Dale district. The succeeding series of terraces denoting a stepped emergence is also in accordance with Rekstad's conclusions, but the critical Tapes Terrace appears unrepresented. Application of Nansen's formula shows that it should be present at a height of 17·6 metres, but there is practically no planation at this level in the locality, and the marine bench at 5 to 7 metres is far too low to fit the case. There is no obvious explanation for this absence of what is a persistent feature elsewhere, and it would be incautious to advance any hypothesis until further detailed work in a number of other valleys has revealed whether it is regionally or only locally missing.

Thanks are offered to Professor Sömme, of Bergen, at whose suggestion the terrace survey of the Dale Valley was undertaken, and also to members of the Le Play Student Group who assisted in the field work.

REFERENCES

NANSEN, F., 1921. The Strandflat and Isostasy. *Skr. Vidensk. Selsk.* Kristiana, No. 11.

REKSTAD, J., 1922. Postglacial Changes of Level in the Scandinavian Peninsula. (English summary of " Norges Hevning after Istiden ".) *Norg. Geol. Unders.*, No. 96. Oslo.

STRÖM, K. M., 1948. The Geomorphology of Norway. *Geogr. Journ.*, 112, pp. 19–27.

UNIVERSITY OF LONDON,
KING'S COLLEGE.

Some Problems of Size and Sorting in Sands

By D. W. Humphries

Abstract

For certain unconsolidated sediments there is a linear relationship between the arithmetic mean size and the " grading factor ", and sediments with an average particle size of 0·2 mm. show the maximum degree of sorting. An hypothesis has been developed to explain this relationship in terms of the environment of deposition.

Introduction

DURING a study of the sedimentation of the Lower Greensand of the south-west corner of the Weald (Humphries, 1953), many mechanical analyses were made. Comparably detailed studies have been made on the Lower Greensand of other parts of the Weald by Gossling, and by Rogers and Richardson (1947), on the Lower Tertiary Beds of the London Basin by Baker (1920) and by Berdinner (1943), and on the Lower Bunter Sandstones of the Midlands by Shotton (1937). All these analyses were examined to determine the existence of a relationship between arithmetic mean size and grading factor; a relationship which might be related to the conditions of deposition.

Statistical Procedure

Two statistics formed the basic data: they were the arithmetic mean size and the " Grading Factor " of Baker (1920). The " Grading Factor " is a measure designed to show how nearly the degree of sorting approaches perfection. A perfectly sorted sediment, according to Baker, is one in which all the grains are of the same size, so that there is no deviation from the mean size and the value of the grading factor would be unity.

Although the grading factor (G_f) was defined empirically by Baker, it is related to the mean deviation thus:—

$$G_f = 1 - \frac{\text{Mean deviation}}{\text{Arithmetic Mean Size}}$$

Scatter diagrams of average size (M_a) versus sorting (G_f) showed a discernible trend in several cases (Text-figs. 1–5) and for these the correlation coefficient (Krumbein and Pettijohn, 1938) was determined. In all cases the 5 per cent level has been taken as significant. Those correlation coefficients which prove to be statistically significant allow of the assumption that a correlation exists in the population from which the sample was drawn. The relationship between the variables is given by the equation for the regression line (Brownlee, 1949, p. 63). The spread of values around this line may be measured by the standard error of estimate (Sy) (Snedecor, 1948, p. 117).

The regression line and the standard error of estimate are plotted on the scatter diagrams. No unusual departures from a linear relationship were found and the trends may be expressed in the form:—

$$G_f = b\,(M_a) + a$$

where b is the slope, and a is the intercept, of the line on the axis of the grading factor.

Description of the Results

Mechanical analyses of sediments from the following horizons have been examined by the method outlined above:—

London Clay Basement Beds Thanet Sands	Tertiary
Folkestone Sands Sandgate Beds Hythe Beds	Cretaceous
Lower Bunter Sandstones	Triassic

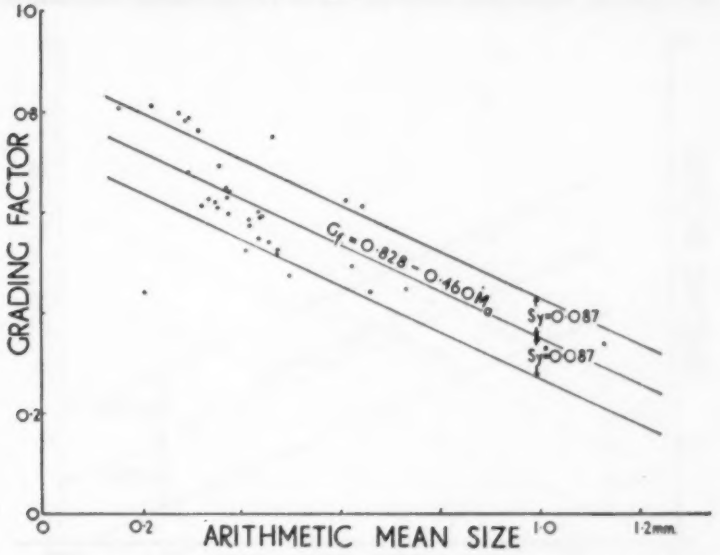
The London Clay Basement Beds (Berdinner, 1943) and Thanet Sands (Baker, 1920) showed a significant direct relationship between size and sorting (Table 1).

Table 1.—Summary of Statistical Examination of Mechanical Analyses.

Horizon and Area.	*Regression Eqn.*	*Sy.*	*r.*	*No. of Samples.*	*p.*	*Mean Ma.*	*Mean Gf.*
Thanet Sands: London Basin.	$G_f = 0{\cdot}492 + 2{\cdot}805M_a$.	0·102	0·695	27	0·001	0·086	0·733
London Clay, Basement Bed: London Basin.	$G_f = 0{\cdot}08 + 4{\cdot}70M_a$.	0·182	0·433	41	0·001	0·055	0·34
Folkestone Sands: South-west Weald.	$G_f = 0{\cdot}828 - 0{\cdot}460M_a$.	0·087	− 0·739	35	0·001	0·460	0·616
Folkestone Sands: North-west Weald.	$G_f = 0{\cdot}661 - 0{\cdot}429M_a$.	0·140	− 0·554	28	0·01	0·458	0·465
Folkestone Sands: Reigate.	$G_f = 0{\cdot}675 - 0{\cdot}429M_a$.	0·137	− 0·608	18	0·01	0·428	0·491
Hythe Beds: South-west Weald	$G_f = 0{\cdot}446 + 1{\cdot}558M_a$.	0·105	0·559	21	0·01	0·151	0·681
Hythe Beds (Bed 1>0·18 mm.): Reigate.	$G_f = 1{\cdot}311 - 3{\cdot}673M_a$.	0·081	− 0·879	7	0·01	0·223	0·472
Hythe Beds (Bed 1<0·18 mm.): Reigate.	$G_f = 4{\cdot}502M_a - 0{\cdot}051$.	0·097	0·643	15	0·01	0·148	0·615

Three groups of analyses from the Folkestone Sands were examined. These were from the south-west Weald, the north-west Weald, and the north Weald. The sands of the south-west Weald were examined by the author in the area between Washington (Sussex) and Greatham (Hampshire). Two strongly contrasting types occur characterized by the presence or absence of strong current-bedding. The current-bedded sands showed correlation between arithmetic mean size and grading factor, while the remainder did not (Text-fig. 1 and Table 1). The second group of analyses was taken from the paper of Rogers and Richardson (1947) who collected their specimens in the north-west Weald around Thursley and Bordon on the borders of Surrey and Hampshire. These authors divided the Folkestone Sands into an

Upper Series consisting largely of pebbly sands with numerous pebble beds, and a Lower Series containing seams and lenticles of silt and clay. The Upper Series showed good correlation (Text-fig. 2 and Table 1), while the Lower Series showed none. The third group relates to the Folkestone Sands of the Reigate–Limpsfield area and is based on the analyses recorded in the laboratory notebooks of the



TEXT-FIG. 1.—Size-sorting relationship in the current-bedded Folkestone Sands in the south-west Weald. (35 samples.)

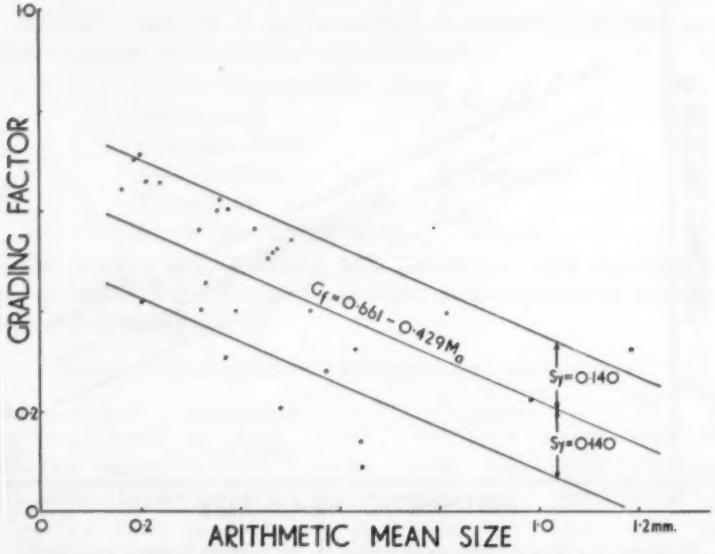
late Mr. Frank Gossling. Correlation was only found in the sands above the Silt Band (Text-fig. 3 and Table 1).

Mechanical analyses of Sandgate Beds from various parts of the Weald were obtained from Gossling's notebooks, from Rogers and Richardson (1947), and from the author's studies. Only small numbers of analyses were available and in no case was significant correlation found. In the case of the Pulborough Sandrock, analysed by the author, there was a striking constancy of grading factor, although the arithmetic mean size varied between 0·08 mm. and 0·16 mm.

Analyses of samples from the Hythe Beds of the south-west Weald showed significant correlation (Text-fig. 4 and Table 1), but the analyses taken from Rogers and Richardson's paper (1947) on the north-west Weald did not. Gossling's unpublished analyses of the Hythe Beds of the north Weald were divided into four groups based on stratigraphic units (Gossling and Bull, 1948). The points on the scatter diagrams

tended to fall into two opposing trends, and on this basis each group was divided into two parts and re-examined. While the results on the whole were disappointing, the lowest beds (the Lower Hythe Sands) showed good correlation for both parts when the division was made at the arithmetic mean size of 0·18 mm. (Text-fig. 5 and Table 1).

As part of a detailed study of the Trias of the Midlands, Shotton (1937) made mechanical analyses of the Lower Bunter Sandstones.



TEXT-FIG. 2.—Size-sorting relationship in Upper Folkestone Sands in the north-west Weald. (28 samples.)

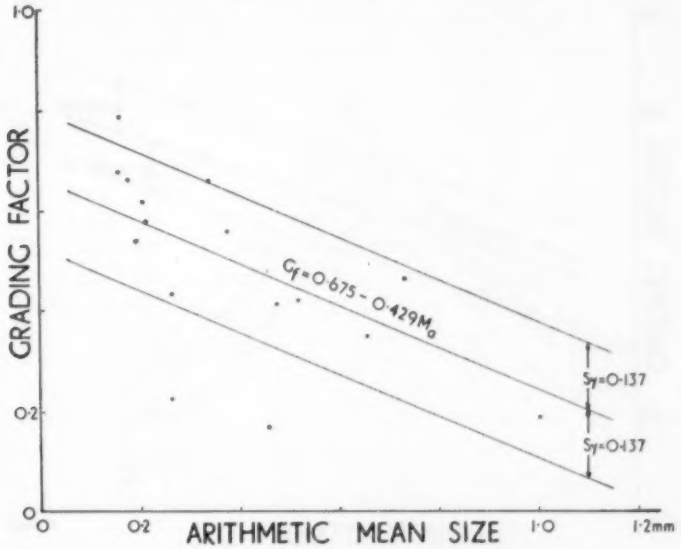
A distinct inverse relationship has been found between size and sorting for those sands with a median diameter greater than 0·2 mm. belonging to the group of " uniform sands ".

DISCUSSION OF THE RESULTS

Over the range of sizes examined (0·04 mm. to 1·2 mm.) the grading factor varies with the arithmetic mean size of the sediment in those cases where correlation occurs. Thus for sediments with an arithmetic mean size less than about 0·2 mm. the grading factor increases as the mean size increases, while for those with an arithmetic mean size greater than about 0·2 mm. the grading factor decreases as the mean size increases. Sediments with an arithmetic mean size of about 0·2 mm. (i.e. fine sand) are therefore the best sorted, while sediments both coarser and finer become progressively more poorly sorted.

Comparable results were obtained by Griffiths (1951) who examined a large number of sediments from the Tertiary beds of the Caribbean area. A similar conclusion was also reached by Inman (1949) from a study of the hydrodynamics of water transport.

In the case of the Folkestone Sands (Table 1) the regression line equation is almost identical in two cases and not greatly different in the third. Furthermore, the standard error of estimate is similar in



TEXT-FIG. 3.—Size-sorting relationship in Upper Folkestone Sands of the Reigate area. (18 samples.)

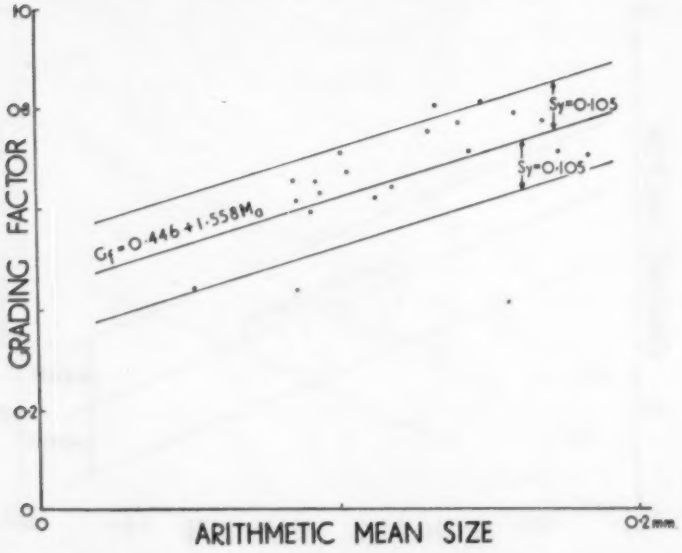
two instances, but in the third case (the south-west Weald) it is much smaller, indicating a greater perfection of the size-sorting relationship.

With very few exceptions, the arithmetic mean size of each Folkestone Sand sample is greater than 0·2 mm. Whether this is characteristic of the current-bedded deltaic sands of the Folkestone Sands alone, or whether it is characteristic of deltaic beds in general, must await the accumulation of many more analyses from this environment. It is noteworthy that the uniform Lower Bunter Sandstones described by Shotton have median diameters generally greater than 0·2 mm. These sands show an almost symmetrical particle size distribution, so that the median diameter is not very different from the arithmetic mean size. These Bunter Sands are aeolian in origin and although the medium of deposition of the Folkestone Sands and the Lower Bunter Sands is probably different, they both show false-

bedding and both generally show an average size of more than 0·2 mm.

The samples from the Tertiary Beds show a trend in the opposite direction to that of the Folkestone Sand, but since the arithmetic mean size shown by these beds is less than 0·2 mm., the result is in accordance with the conclusions given above.

A further point of interest concerns the Hythe Beds. In the south-



TEXT-FIG. 4.—Size-sorting relationship in Hythe Beds in the south-west Weald. (21 samples.)

west Weald good correlation was found, and although the specimens were collected over a considerable area, very few exceed 0·2 mm. in mean size. In the north-west Weald it is notable that only one specimen had an arithmetic mean size less than 0·2 mm., and that no correlation occurred. In the north Weald good correlation was obtained only in the Lower Hythe Sand as mentioned above. Here the results fell into two distinct groups greater and less than 0·2 mm. Since the Hythe Beds of the north-west and south-west Weald did not show this two-fold division it may be proposed that the conditions of deposition in the three areas were different.

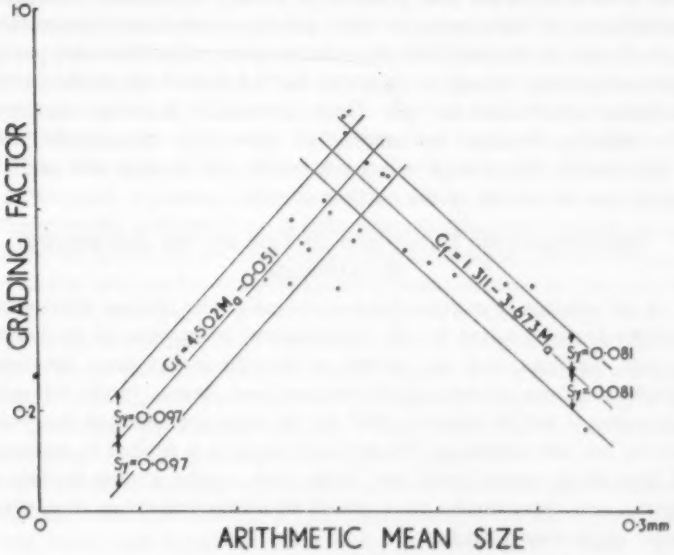
FACTORS INVOLVED IN THE SORTING OF SEDIMENTS

Among the many factors controlling the erosion and deposition of sands in a current of water the more important are:—

(1) Erosion velocity.
(2) Specific gravity and shape of particles.
(3) The turbulence of the transporting agent.

Of these factors, the erosion velocity is the one most important in the development of the hypothesis to explain the size-sorting relationship.

Experimental work of Hjulström (1935) has shown that for uniformly sorted material having a diameter greater than 0·25 mm.



TEXT-FIG. 5.—Size-sorting relationship in Hythe Beds: Bed 1, of Reigate area. (22 samples.)

the velocity required to cause the erosion of such particles increases with increase in the size of the particles. On the other hand, for particles smaller than 0·25 mm. the velocity required to move the particles increases with decrease in the size of the particles. Inman (1949) has also determined the minimum or threshold velocities required to erode particles and has concluded that the threshold velocity gradually decreases with decreasing grain size until a diameter of approximately 0·18 mm. is reached. At this point the sediment becomes effectively "smooth" and the current stream is unable to remove the finer particles unless the current velocity is again increased. According to Inman the erosion velocity for particles of 2 mm. diameter is about 4 cm./sec., for 0·18 mm. particles about 1·5 cm./sec., and for 0·01 mm. particles about 6 cm./sec. The velocity required to erode clay particles of 0·001 mm. is said by Hjulström to be about

250 cm./sec. It must be remembered that both Inman's and Hjulström's experimental work was carried out with uniformly graded material, in which the grading factor would be very close to unity, and not with naturally occurring sands possessing varying grading factors. However, the fact that the velocity required to move sand of a single grade is a minimum when the particle size is about 0·2 mm. and the evidence that the grading factor reaches a maximum when the arithmetic mean size is about 0·2 mm. is either a remarkable coincidence or there must be some definite connection between them.

It should be stressed that the relation given above between particle size and current velocity is only true for the case in which the particle is being eroded from its bed. Once the particle is being transported the velocity required to keep it in motion is considerably less. Furthermore, the current velocity at which the particle will settle on to the bed decreases as the particle size decreases.

Development of Hypothesis to Explain the Size-sorting Relationship

In an attempt to explain the corroborative size sorting relationship independently reached by the experimental researches of Hjulström, Inman, Griffiths, and the author, a hypothesis has been developed which takes into account the factors outlined above. In the following discussion it will be assumed that the particles are constant in specific gravity and are spherical. Thus, the discussion is limited to materials of fine silt to coarse sand size, since they consist almost entirely of quartz, and approximate more closely to a spherical shape than either larger or smaller particles.

The argument is based on the supposition that sediments with an arithmetic mean size less than 0·2 mm. or greater than 0·2 mm. will be more difficult to erode by water than those with a mean size approximating to 0·2 mm., as in the case of materials of a single grade size.

In a number of cases there is a predictable relationship between arithmetic mean size and grading factor, as follows:—

I. Sorting of sediment during transport.
II. Sorting of sediment which remains after erosion.
  (i) Arithmetic mean size of original sediment about 0·2 mm.
  (ii) Arithmetic mean size of original sediment less than 0·2 mm.
  (iii) Arithmetic mean size of original sediment greater than 0·2 mm.
III. Sorting of sediment removed by erosion.
  (i) Arithmetic mean size of original sediment about 0·2 mm.
  (ii) Arithmetic mean size of original sediment less than 0·2 mm.
  (iii) Arithmetic mean size of original sediment greater than 0·2 mm.

Case I. Sorting of sediment during transport.—Under normal conditions of denudation the source sediment is likely to consist of poorly graded material with a considerable range of particle sizes (Krumbein and Tisdel, 1940). Let this be acted upon by a current of water of sufficient erosive power to carry with it material from fine silt to coarse sand in size. When this current is checked the coarsest material is laid down first and the finest material is carried furthest. This is a familiar concept but it must be realized that the current does not decrease at a steady rate since the water is in turbulent motion. This implies that even over small distances the velocity of the water may vary considerably and will allow a range of sizes of particles to be deposited. It would, therefore, appear that the best graded material would be deposited where the turbulence was least. The grading of the deposited material would only be preserved if it was not subjected to subsequent erosion. This condition would be fulfilled at least partially under conditions of deltaic sedimentation, where each layer of material is quickly covered by a subsequent layer. Since the size of particles deposited is in approximately linear relation to the current velocity, we may expect a random variation in the average size of particles deposited in deltaic conditions due to the random variations of the current strength. As mentioned earlier, the degree of grading appears to be inversely related to the degree of turbulence, itself in part controlled by current velocity. There will thus be an inverse relationship between grading factor and average size.

Case II (i). Sorting of sediment which remains after erosion. Arithmetic mean size about 0·2 mm.—Suppose that the current velocity is just below the threshold velocity for particles of 0·2 mm. The sediment is stable and none of it will be removed by the current. If the velocity of the current is now increased sufficiently to begin eroding the sediment, the grains of 0·2 mm. diameter will steadily be removed. The arithmetic mean size of the remaining material will tend to rise slightly, owing to the greater influence on average size of one large particle compared with the influence of a single small particle. The grading factor will tend to decrease as the end members become more dominant. Ultimately the sediment will consist of a mixture of two grain size distributions since the fine sand will be totally removed and the sediment will consist of very fine particles and also large particles with no intermediate sized ones. In reaching this state the sediment will have passed from a unimodal distribution to a bimodal one. This may in part explain the occurrence of bimodal sediments which are normally attributed to the mixing of sediments.

Case II (ii). Sorting of sediment which remains after erosion. Arithmetic mean size of original sediment less than 0·2 mm.—As the current strength increases the particles of about 0·2 mm. are the first

to be removed, but in this case they are the end members of the distribution. The arithmetic mean size therefore decreases, while the grading factor tends to rise.

Case II (iii). Sorting of sediment which remains after erosion. Arithmetic mean size of original sediment greater than 0·2 mm.—Again the particles of about 0·2 mm. are the first to be removed, so the arithmetic mean size tends to rise as does the grading factor.

Summarizing these three cases for sediments undergoing erosion, the grading factor of the remaining material tends to rise, except where the bulk of the material has a size of about 0·2 mm. when the grading factor tends to fall. At the same time the arithmetic mean size tends to rise for all sediments with an initial mean size greater than 0·2 mm., and tends to fall when the initial mean size is less than 0·2 mm.

Case III (i). Sorting of sediment removed by erosion. Arithmetic mean size of original sediment about 0·2 mm.—The material initially removed consists of grains of 0·2 mm. or thereabouts only and its grading factor will therefore be high. As the velocity of the eroding current increases, more particles both greater and less than 0·2 mm. will be taken up and the grading factor will tend to fall, while the arithmetic mean size will remain roughly constant.

Case III (ii). Sorting of sediment removed by erosion. Arithmetic mean size of original sediment less than 0·2 mm.—The material removed will at first show a high grading factor since it will consist largely of 0·2 mm. particles, but as erosion proceeds the material being transported will show a falling grading factor and a falling mean size as more and more finer-grained material is picked up.

Case III (iii). Sorting of sediment removed by erosion. Arithmetic mean size of original sediment greater than 0·2 mm.—In the final case the initial material taken up will have a high grading factor and a mean size of 0·2 mm. but as erosion proceeds the coarser material will be removed and the grading factor will decrease while the mean size rises.

Summarizing the three cases of material in transport, with increasing arithmetic mean size, the grading factor rises to a maximum when the mean size is about 0·2 mm., and then decreases.

Comparison of the two sets of cases shows that the relationship between arithmetic mean size and grading factor for eroded sediments is the converse of that for the material taken into suspension for transport.

The sediment which has suffered erosion will tend to be preserved if a state of equilibrium is approached between the water velocity and the sizes of the particles remaining. Should the velocity increase sufficiently the whole of the sediment may be removed. If, on the other hand, the velocity should fall erosion will cease and sediment

brought by the slower moving current will entomb and preserve the eroded sediment.

In order to retain the grading of the material taken up by an eroding water current, it is necessary that it suffers little if any sorting during transport and is deposited rapidly, so that sorting during the process of deposition does not occur. This condition could arise if the material is not transported for any great distance and is suddenly brought into an area of still water.

Normally a river flowing into the sea continues as a unit for some distance before being completely dispersed. Now suppose that the river enters an estuary. As the tide rises at the mouth of the estuary it will be opposed to the river current and the water in the estuary will be at relative rest, giving conditions for a brief time in which the sediment could be deposited without further sorting. Once the sediment has settled to the bottom of the estuary it would not be readily subject to erosion when the tide turned and the velocity of the water increased. The material coarser than 0·2 mm. will, of course, also be deposited in the estuary but will be more easily eroded and ultimately carried out to sea. It seems likely, therefore, that sandy material is only a transient feature of an estuary.

Since estuaries are a result of rise in sea-level with a consequent reduction in velocity of streams, it is possible that in many cases little material greater than 0·2 mm. will be delivered to the estuary initially.

In the case of a stream terminating in a delta the velocity of the current will be checked sufficiently for the bulk of the sediment load to be deposited rapidly, but since the stream is not brought to a complete standstill, the fine material in suspension will be carried across the delta.

Both the coarse material leaving an estuary and the fine material crossing a delta would finally come under the prolonged action of the sea. In the absence of marine currents it seems likely that the sediments would become thoroughly mixed and the relationship between arithmetic mean size and grading factor is likely to be a random one for all values of the mean size.

The hypothesis as developed has shown that under certain conditions a relationship is to be expected between arithmetic mean size and grading factor, and that this relationship takes definite forms in certain environments. These may be summarized as follows:—

(1) Deltaic environment. An inverse relationship occurs between arithmetic mean size and grading factor during deposition.

(2) Estuarine environment. Direct relationship between arithmetic mean size and grading factor of deposited material when the mean size is less than 0·2 mm. Inverse relationship when mean size is greater than 0·2 mm. (if such sediments are present).

(3) Marine environment. Probably no relationship between arithmetic mean size and grading factor.

Comparison of Hypothesis with Evidence of Mechanical Analysis

The three sets of analyses of sands from the Folkestone Sands described earlier show an inverse relationship between arithmetic mean size and grading factor and a minimum mean size of about 0·2 mm. The Folkestone Sands show well-developed current-bedding with a constant direction of the foreset beds, suggestive of deposition in a deltaic environment. This compares favourably with Case I of the hypothesis although the latter does not account for the absence of material with a mean size less than 0·2 mm.

The relationship between size and sorting developed in the hypothesis for the sediment which remains after erosion is not exemplified by the mechanical analyses described earlier.

The relationship developed for size and sorting of the sediment which is removed during erosion is similar to that obtained from the Hythe Beds, the Thanet Sands, and the London Clay Basement Bed (cf. Text-figs. 4 and 5, and Table 1). The hypothesis indicated that such a relationship would occur in an estuarine environment. Although the Hythe Beds and the Thanet Sands are regarded as entirely marine, there is evidence that they were laid down in shallow tidal waters. Under such conditions, periods of slack water, similar to those occurring in an estuary, would permit sorting and deposition of sediments comparable to that postulated for estuarine conditions.

Thus, there is good agreement between the hypothesis, which was developed independently of the mechanical analyses, and the information derived from the field and laboratory examination of the unconsolidated rocks described above.

Conclusion

It is appreciated that much of the hypothesis is not based on complete experimental evidence. In many ways it may be untenable. For example, it is unable to explain the enormous thicknesses of fine-grained sediments described by Griffiths (1951) from the Caribbean which show a direct relation between size and sorting, unless it is postulated that the sediments were " poured " into a basin of deposition so rapidly that their direct size-sorting relation due to their initial erosion was preserved. They were certainly not preserved in an estuary. Nor can the hypothesis predict the precise mathematical relationship between arithmetic mean size and grading factor in terms of the constants of the regression line. This results from inadequate

quantitative information concerning the numerous factors involved in the sorting of sediments.

However, the hypothesis of sorting outlined above explains the results of mechanical analysis and while such an hypothesis may not be the only one, in the absence of any other, it is suggested that it provides a convenient working basis.

ACKNOWLEDGMENTS

The author wishes to express his thanks to Dr. J. F. Kirkaldy and to Professor L. R. Moore for their interest and encouragement. Acknowledgment is made to the University of London and to Queen Mary College, University of London, for grants. For making available the notebooks of the late Mr. Frank Gossling which were deposited in the archives of the Weald Research Committee, the author is indebted to Dr. Kirkaldy.

REFERENCES

BAKER, H. A., 1920. On the investigation of the mechanical composition of loose arenaceous sediments. *Geol. Mag.*, lvii, 363, 411, and 463.

BERDINNER, H. C., 1943. Contributions to a study of laboratory method in mechanical analysis together with an account of the mechanical constitution of certain Eocene sediments. *M.Sc. Thesis.* (University of London Library.)

BROWNLEE, K. A., 1949. *Industrial Experimentation.* H.M.S.O.

GOSSLING, F., 1929. Geology of the country around Reigate. *Proc. Geol. Assoc.*, xl, 197.

GOSSLING, F. (the late), and BULL, A. J., 1948. The structure of Tilburstow Hill, Surrey. *Ibid.*, lix, 131.

GRIFFITHS, J. C., 1951. Size versus sorting in some Caribbean sediments. *Journ. Geol.*, lix, 211.

HJULSTROM, F., 1935. Studies of the morphological activity of rivers as illustrated by the River Fyrias. *Bull. Geol. Inst. Upsala*, xxv, 221–527.

HUMPHRIES, D. W., 1953. The lithology and conditions of deposition of the Lower Greensand of the South West Weald. *Ph.D. Thesis.* (University of London Library.)

INMAN, D. L., 1949. Sorting of sediments in the light of fluid mechanics. *Journ. Sed. Pet.*, xix, 51.

KRUMBEIN, W. C., and PETTIJOHN, F. J., 1938. *Manual of Sedimentary Petrography.* New York and London.

KRUMBEIN, W. C., and TISDEL, V. W., 1940. Size distributions of source rocks of sediments. *Amer. Journ. Sci.*, 238, 296–305.

ROGERS, H. S., and RICHARDSON, J. A., 1947. Mechanical analysis of the Lower Greensand of North West Surrey. *Proc. Geol. Assoc.*, lviii, 259.

SHOTTON, F. W., 1937. The Lower Bunter Sandstones of North Worcestershire and East Shropshire. *Geol. Mag.*, lxxiv, 534.

SNEDECOR, G. W., 1948. *Statistical Methods.* Iowa.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF SHEFFIELD.

Rare Alkali Elements in Trilobites

By W. S. McKerrow, S. R. Taylor, Audrey L. Blackburn, and L. H. Ahrens

(PLATE XIII)

Abstract

Li, Rb, and Cs were determined spectrographically in twenty-eight trilobites, two xiphosurida, four insects, four crustacea, and six brachiopods. The sediments associated with fifteen trilobites were also analysed. Compared with igneous and sedimentary rocks, the trilobites were characteristically enriched in cesium relative to rubidium and potassium. Thus, the K/Rb ratios were normal, but the Rb/Cs ratios were anomalously low. The evidence is considered to favour the view that cesium has been preferentially concentrated by trilobites during growth. The matrices had Rb/Cs ratios similar to normal sedimentary rocks.

Introduction

In contrast to the large number of trace element determinations on plants, animals, soils, and rocks, few have been made on fossils. Clarke and Wheeler (1922) and Vinogradov (1953) have summarized data on major constituents in marine organisms. Fearon (1946) and Heilbrunn (1952) have discussed the distribution of the alkali metals in organisms and Fearon (1946, p. 19) states that cesium is a doubtful constituent in animals.

Chave (1954) has studied the distribution of magnesium in modern marine organisms. Webb (1937) used a spectrographic method to investigate twenty-three elements in modern marine invertebrates. Richards (1951) in a survey of the integument of arthropods, quotes Clarke and Wheeler's (1922) data.

Kulp *et al.* (1952) have determined strontium in a large number of fossils finding that, despite considerable variation, they contain on the average, twice as much strontium as the surrounding carbonate matrix. No references have been found to work on the rare alkali elements in fossils.

Since potassium-argon methods of age determinations have recently been applied to glauconites (Lipson, 1956) it was decided to check the potassium content of some fossils. Preliminary spectrographic determinations of the alkali elements were consequently made on exoskeletons of a brachiopod (*Lingula*), a lamellibranch (*Gryphaea*), and a trilobite (*Calymene*). In examining the trilobite spectra for potassium, the cesium line at 8521 A., normally faintly visible if at all in the spectra of igneous and sedimentary rocks, was seen to be very strong relative to the potassium and rubidium lines. This indicated that cesium was enriched in the trilobite to a surprising

extent compared with its normal geochemical distribution in rocks, or with its abundance relative to rubidium. Consequently a survey was made of some trilobites and other arthropods to determine the extent of this enrichment. Of four brachiopod genera also examined, *Lingula*, the only chitinous form, showed some enrichment in cesium (Table 3).

Dr. C. J. Stubblefield has read the manuscript and the authors are grateful for his suggestions. We also wish to thank Professor L. R. Wager for his continued interest in the work.

Analytical Method

The samples were ground in an agate mortar to pass 120 mesh bolting cloth. Analyses were carried out on a Hilger large Littrow spectrograph (glass optics) in the wavelength range 4600–9600 A. The powders were loaded in Johnson Matthey graphite anodes (internal diameter 4 mm., depth 2 mm., minimum wall thickness). Champion carbon cathodes (5 mm. diameter) sharpened to a point were used, and the specimens were arced to completion at 3 amp. D.C. (anode excitation). The arc gap was 10 mm. and light from the centre two-thirds of the arc was allowed to fall on the slit. Slit width was 20 microns, and a seven-step sector was used to control intensity. Kodak II N plates were processed for five minutes in Kodak D-19 B developer at 20° C.

Plate calibration was by the self-calibration method (Ahrens, 1950, pp. 136–8). Standards were made by the addition of Johnson Matthey "Specpure" NaCl, KCl, RbCl, and Cs_2CO_3 to a base of powdered *Gryphaea*.

Lines used Li 6103, 6707
K 7664, 7699
Rb 7800, 7947
Cs 8521.

Some specimens burnt evenly in the arc, but a number gave an erratic burn and reproducibility was consequently poor, and the magnitudes reported in this paper are approximate only. The Rb/Cs ratio is, however, a better measure of relative enrichment than the absolute amounts present. Apart from some possible systematic error, which it is not possible to assess, the reproducibility per determination is estimated as $\lambda' = 2$ (for discussion of expressing reproducibility in this form see Ahrens, 1954, p. 46).

Specimens Analysed

Li, Na, Rb, and Cs were determined in twenty-eight trilobites (Table 1), two xiphosurans, four insects, four crustacea (Table 2), and six brachiopods (Table 3): the matrices adjacent to fifteen of

TABLE 1.—ANALYSES OF TRILOBITES. THE NUMBERS ARE THOSE OF THE OXFORD UNIVERSITY MUSEUM GEOLOGICAL COLLECTION
Amounts in parts per million

No.	Genus and Species	Part of Body	Age	Locality	Li	Na	Rb	Cs	Rb/Cs
A468	*Paradoxides davidis*	thorax	M. Cambrian	S. Wales	10	—	6·5	25	0·26
B124	*Asaphus* sp.	pygidium	? Llandilo		(1)	—	(4)	(3)	(1·3)
B125	*Trinucleus fimbriatus*	rim of cephalon	Lower Caradocian	Llandrindod Wells, Radnorshire	6	—	16	20	0·8
B117	*T. fimbriatus*	cephalon and pygidium	Lower Caradocian	Llandrindod Wells	8	—	9	4	2·25
B104	*Onnia* (*Trinucleus*) cf. *superba*	cephalons	Upper Caradocian	(same specimen as B118) Shropshire	50	2700	15	(2)	(7·5)
B127	*Onnia* (*Trinucleus*) *gracilis*	cephalon	Upper Caradocian	Shropshire	10	—	5	< 1	> 5
B126	*Trinucleid*	cephalons	Ashgillian	Westmorland	40	—	36	(< 3)	> 12
B118	*Platycalymene duplicata*	cephalon	Lower Caradocian	Llandrindod Wells	8	—	9	(0·5)	(18)
B128	*Flexicalymene* sp.	cephalon (about 50 per cent matrix)	Upper Caradocian	(same specimen as B117) Shropshire	15	—	(6)	< 1	> 6
C173	*Calymene blumenbachi*	all parts	Woolhope Limestone	Old Radnor	25	—	100	80	1·25
C172	*C. blumenbachi*	thorax and pygidium	Wenlock Limestone	Dudley	12	—	40	50	0·80
C174	*C. blumenbachi*	fixed cheek	Wenlock Limestone	Dudley, locality 1	6	1700	12	4	3·0
C175	*C. blumenbachi*	glabella	Wenlock Limestone	Dudley, locality 1	12	2300	45	14	3·2
C176	*C. blumenbachi*	cephalon	Wenlock Limestone	Dudley, locality 2	8	1500	18	35	0·51
C177	*C. blumenbachi*	glabella	Wenlock Limestone	Dudley, locality 2	12	2700	60	17	3·5
C178*a*	*C. blumenbachi*	glabella	Upper Silurian	(same specimen as C178*b*)	6	1150	5	(1)	(5)
C178*b*	*C. blumenbachi*	pygidium	Upper Silurian	(same specimen as C178*a*)	8	1200	7·5	(1)	(7·5)
C186	*Acidaspis* sp.	cephalon	Wenlock Shale	Malvern	4	—	10	8	1·25
C187	*Cheirurus bimucronatus*	all parts	Wenlock Shale	Malvern	25	—	50	10	5·0
C188	*Deiphon forbesi*	glabella	Wenlock Shale	Malvern	15	—	90	250	0·36
C169	*Encrinurus punctatus*	cephalon and thorax	Wenlock Shale	Malvern	20	—	40	4	10·0
C182	*E. punctatus*	cephalon	Wenlock Limestone	Dudley, locality 2	8	1450	8·5	18	0·47
C183	*Dalmanites vulgaris*	pygidium	Wenlock Shale	Malvern	5	—	3·5	3·5	1·0
C184	*D. vulgaris*	pygidium	Wenlock Limestone	Dudley, locality 1	12	2500	32	33	0·97
C185	*D. vulgaris*	pygidium	Wenlock Limestone	Dudley, locality 2	3	1400	10	5	2
C167	*Acaste downingiae*	all parts	Wenlock Shale	Malvern	20	—	50	7	7·1
C180	*A. downingiae*	pygidium	Wenlock Limestone	Dudley, locality 1	10	2600	42	10	4·2
C181	*A. downingiae*	pygidium	Wenlock Limestone	Dudley, locality 1	10	2200	32	24	1·33
C179	*A. downingiae*	pygidium	Wenlock Limestone	Dudley, locality 2	15	1600	12	7	1·7

the trilobite exoskeletons were also analysed (Table 4). The specimens selected are from widely separated groups of Arthropods, but include ten trilobites from a single rock unit, the Nodular Beds of the Wenlock Limestone (Upper Silurian) at Dudley, Staffordshire, England. These latter were collected by two of the authors on the west flank of the Wren's Nest anticline from two localities less than a quarter of a mile apart:—

(1) At the top of the Nodular Beds 350 yards north-east of the limeworks (National Grid: 935920); here the lithology corresponds to Butler's (1940) type B, and the bedding is well marked. Collections were made at two horizons 6 inches apart over an area of about 12 feet square.

TABLE 3.—ANALYSES OF BRACHIOPODS

Amounts in parts per million

	Rb	Cs
Class INARTICULATA (shells usually with chitin)—		
(1) *Lingula* Up. Sil.	5	15
(4) *Lingula* Eocene	3	7
Class ARTICULATA (calcareous shells)—		
Suborder TEREBRATULOIDEA—		
(17) *Epithyris oxonica* Great Oolite, Oxon .	< 1	n.d.
Suborder TEREBRATELLOIDEA—		
(19) *Ornithella obovata*—Cornbrash . .	n.d.	n.d.
(20) *Ornithella bathonica* Fuller's Earth Rock—Bruton, Somerset	4	n.d.
Suborder RHYNCHONELLOIDEA—		
(21) *Rhynchonelloidella smithi*—Fuller's Earth Rock—Bruton, Somerset . . .	5	3

n.d. = not detected.

(2) At a middle horizon in the Nodular Beds about 150 yards south of the limeworks (935916); here again the lithology corresponds to type B, but the beds are more nodular and the bedding planes less well defined. The specimens were collected over a horizontal range of about 15 yards.

Among other specimens analysed are some belonging to the Grindrod Collection from the Wenlock Shale of the Malverns (tunnel section).

COMPARISON BETWEEN TRILOBITES AND ENCLOSING MATRIX

Plate XIII shows spectra of *Deiphon* (A) and its enclosing matrix (B). It is clearly seen from examination of the relative intensities of the potassium, rubidium, and cesium lines marked, that while K and Rb

TABLE 2.—ANALYSES OF ARTHROPODS OTHER THAN TRILOBITES. Amounts in parts per million

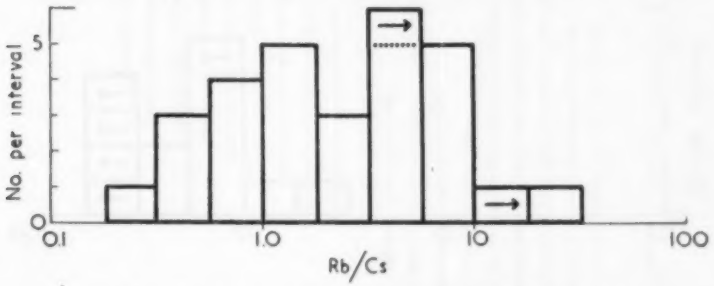
No.	Genus and Species	Part of Body	Age	Locality	Environment	Li	Na	Rb	Cs	Rb/Cs
			XIPHOSURIDA							
E1435	*Euproops* sp.	carapace and trunk	Upper Carbonif.	—	non-marine	10	—	14	(3)	(4·7)
RQ2	*Limulus polyphemus*	carapace	Modern	—	marine	< 0·2	—	< 1	< 1	
			CRUSTACEA							
RZ19	*Carcinus maenus* (crab)	carapace	Modern	—	marine	1	—	< 1	(3)	< 0·3
RZ18	*Homarus vulgaris* (lobster)	cephalothorax and claw	Modern	—	secondarily marine	8	4700	< 1	< 1	
RZ16	*Scyllarus latus* (rock lobster)	cephalothorax	Modern	Mediterranean	marine	4	2700	(1)	< 1	> 1
RZ17	*Astacus fluviatilis* (crayfish)	cephalothorax	Modern	England	non-marine	1	1150	< 1	< 1	
			INSECTA							
RZ20	Cockroach : *Periplaneta americana*	carapace and wing	Modern	—	terrestrial	< 0·2	—	< 1	< 1	
RZ14	Beetles : *Blaps mucronata*	head and wing case	Modern	Britain	terrestrial	(0·3)	1300	(< 1)	< 1	
RZ15	*Cetonia aurata*	all hard parts	Modern	New Forest	terrestrial	< 0·2	820	3·5	< 1	> 3·5
RX11	Cetoniid	all hard parts	Modern	Uganda	terrestrial	< 0·2	680	(2)	(1)	(2)

TABLE 4.—ANALYSES OF TRILOBITE MATRICES. Amounts in parts per million

No.	Associated Fossil	Age	Locality	Li	Na	Rb	Cs	Rb/Cs
A468	*Paradoxides davidis*	M. Cambrian Shale	South Wales	10	—	50	4	12·5
B124	*Asaphus*	M. Ordovician Limestone		1	—	< 1	< 1	—
B125	*Trinucleous fimbriatus*	Lower Caradocian Shale	Llandrindod Wells	15	—	30	< 1	> 30
B117/8	*T. fimbriatus* and *Platycalymene duplicata*	Lower Caradocian Shale	Llandrindod Wells	10	—	30	< 1	> 30
B104	*Onnia* cf. *superba*	Upper Caradocian Shale	Shropshire	20	—	30	< 1	> 30
B127	*Onnia gracilis*	Upper Caradocian Shale	Shropshire	15	—	30	< 1	> 30
C186	*Acidaspis*	Wenlock Shale	Malvern	10	—	15	< 1	> 15
C187	*Cheirurus bimucronatus*	Wenlock Shale	Malvern	15	—	40	(2)	(20)
C188	*Deiphon forbesi*	Wenlock Shale	Malvern	5	—	25	(2)	(12)
C183	*Dalmanites vulgaris*	Wenlock Shale	Malvern	1	—	< 1	< 1	—
C172	*Calymene blumenbachi*	Wenlock Limestone	Dudley	25	—	60	14	4·3
C174/5	*C. blumenbachi*	Wenlock Limestone	Dudley, locality 1	30	3600	50	(3)	(16·7)
C176/182	*C. blumenbachi* and *Encrinurus punctatus*	Wenlock Limestone	Dudley, locality 2	25	3100	55	(3)	(18·3)
C181	*Acaste downingiae*	Wenlock Limestone	Dudley, locality 1	30	2500	62	10	6·2
E1435	*Euproops*	Upper Carboniferous Shale		(10)	—	(10)	< 1	> 10

are present in the same relative amounts, cesium is strikingly enriched in the fossil.

Text-fig. 1 is a histogram showing the distribution of the Rb/Cs ratio in twenty-eight trilobites. Attention has been paid to this ratio rather than to the actual amounts of Rb and Cs because it is more accurately estimated. The graph has been constructed on semi-logarithmic paper (in order to give equal portrayal of the ratios above and below unity). A power factor of 1·78 was chosen to give the interval, each cycle thus containing four classes. The values of Rb/Cs in the trilobites examined range from 0·26 to $>$ 18. The uncertainty of the upper limit is due to the fact that Cs is below its detection limit in two specimens and thus the ratios given are minimum values; these specimens are indicated on the graph by arrows. Neglecting these (which may lie anywhere on the graph to the right of the classes



TEXT-FIG 1.—Rubidium cesium ratio in trilobites.

indicated) it can be seen that the distribution of the ratios is essentially unimodal, though the class 1·78–3·16 has a lower reading than its neighbours.

Text-fig. 2 is a histogram showing the distribution of Rb/Cs in thirteen matrices. As in Text-fig. 1, the arrows indicate minimum values of five specimens. Here the mode occurs between 10 and 17·8, and the ratio ranges from 4·3 to over 30; these are very distinctly higher values than those of the trilobites. Two trilobites (*Asaphus* B.124 [1] and *Dalmanites* C.183) occur in limestone matrices which have less than one part per million of both Rb and Cs, and hence the Rb/Cs ratios are not determinable.

Further comparison between exoskeleton and matrix is portrayed in Text-fig. 3; here the Rb/Cs value is seen in each case to be lower than the surrounding matrix. The length of the line between each pair corresponds to the ratio between Rb/Cs for the matrix and

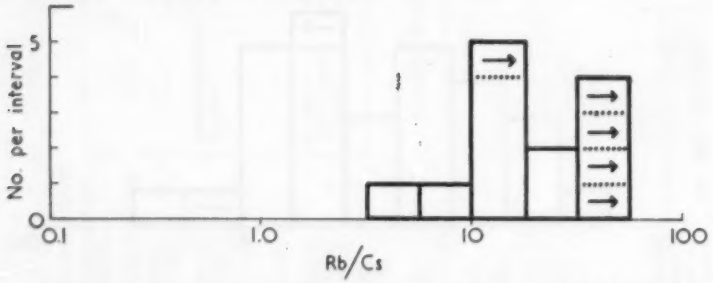
[1] The numbers refer to specimens in the Oxford University Museum collections.

Rb/Cs for the shell. The values of this matrix-shell ratio range from 48·1 (*Paradoxides*) to 4·0 (*Acaste* and *Cheirurus*); the mean value is 15·5. One result worthy of comment is that the matrix-exoskeleton ratios of five specimens are very much larger than the remainder; the bottom five shown on Text-fig. 3 have a ratio of over 33, while the rest (with two possible exceptions where minimum values only are known) have a matrix-exoskeleton ratio of less than 11.

Differences between Trilobite Analyses

(*a*) *Different Parts of the same Trilobite.*

Indirect evidence that there is little or no difference between the different parts of a trilobite can be inferred from a study of the distribution of the Rb/Cs ratios: analyses of pygidia have a similar range and mode to analyses of cephala. To confirm this the glabella



Text-fig. 2.—Rubidium cesium ratio in sediments associated with trilobites.

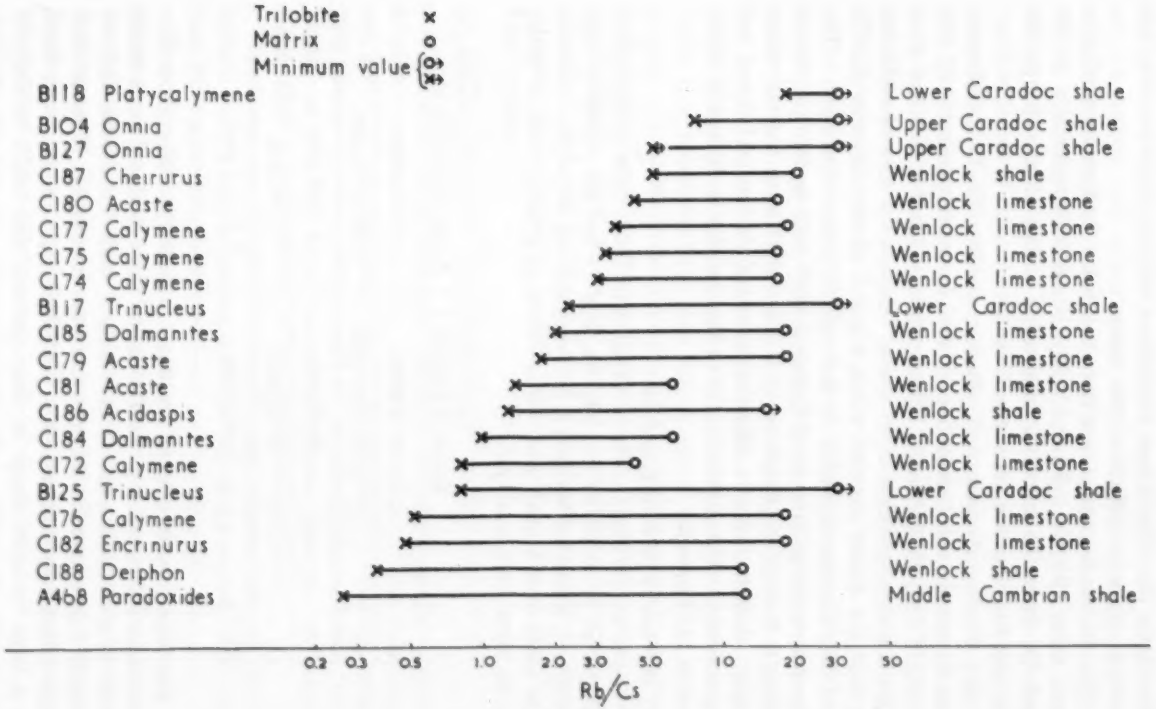
and the pygidium of a *Calymene blumenbachi* C.178 were analysed separately. There were no differences in the estimated amounts of Cs, Rb, Na, and Li outside the limits of experimental error. Greater differences were noted among the cephala of four *Calymenes* collected at Dudley, e.g. Cs ranged from 5 to 35 ppm., Rb from 12 to 60 ppm., and the Rb/Cs ratio from 0·51 to 3·5.

(*b*) *Differences between Genera from the Same Locality.*

(i) *Lower Caradocian Shale.*—Specimens of *Trinucleus fimbriatus* and *Platycalymene duplicata* (B.117, B.118) occurring in the same bed within 2 inches of each other show identical values of Rb and Li but the calymenid has an Rb/Cs ratio eight times greater than the *Trinucleus* (Cs, 4 ppm. compared with Cs, 0·5 ppm.).

(ii) *Wenlock Nodular Beds, Dudley, Locality* 1.—Collections were made at two horizons 6 inches apart; two *Calymene* and one *Acaste* came from the lower horizon and another *Acaste* and a *Dalmanites* from the higher (C.174, C.175, C.180, C.181, and C.184 respectively).

The *Calymene* specimens have similar Rb/Cs ratios (3·0 and 3·2)


Trilobite
Matrix
Minimum value
B118 Platycalymene
B104 Onnia
B127 Onnia
C187 Cheirurus
C180 Acaste
C177 Calymene
C175 Calymene
C174 Calymene
B117 Trinucleus
C185 Dalmanites
C179 Acaste
C181 Acaste
C186 Acidaspis
C184 Dalmanites
C172 Calymene
B125 Trinucleus
C176 Calymene
C182 Encrinurus
C188 Delphon
A468 Paradoxides
Lower Caradoc shale
Upper Caradoc shale
Upper Caradoc shale
Wenlock shale
Wenlock limestone
Wenlock limestone
Wenlock limestone
Wenlock limestone
Lower Caradoc shale
Wenlock limestone
Wenlock limestone
Wenlock limestone
Wenlock shale
Wenlock limestone
Wenlock limestone
Lower Caradoc shale
Wenlock limestone
Wenlock limestone
Wenlock shale
Middle Cambrian shale
0.2 0.3 0.5 1.0 2.0 3.0 5.0 10 20 30 50
Rb/Cs

TEXT-FIG. 3.

but the actual values for Rb and Cs are very different (Rb 12, Cs 4; Rb 45, Cs 14). The *Acaste* that occurs with the *Calymene* does not show a significant difference from them.

The *Dalmanites* and *Acaste* from the higher horizon are similar to each other (Rb/Cs 0·97 and 1·33), but differ considerably in Rb and Cs from the trilobites collected 6 inches lower, though the Na and Li values are not very different.

(iii) *Wenlock Nodular Beds, Dudley, Locality* 2.—Two *Calymene*, one *Encrinurus*, one *Dalmanites*, and one *Acaste* were collected (C.176, C.177, C.182, C.185, and C.179 respectively) from beds 5 feet thick over a horizontal range of 15 yards. Though the area of collection is large the *Acaste* occurred within 6 inches of one *Calymene* (C.177) and the *Encrinurus* within 1 inch of the other *Calymene*. The *Encrinurus* and its associated *Calymene* both have an Rb/Cs ratio of about 0·5 while the *Calymene* and *Acaste* that occur together show higher, though distinctly different, values of this ratio (3·5 and 1·7 respectively). The *Dalmanites* from this locality is distinct in being low in Li (3 ppm.).

(*c*) *Differences between Localities.*

The collection made at the two Dudley localities show no significant differences in values of Cs, Rb, Na, and Li but the trilobites from locality 1, where the bedding is more regular and where the collection was made over a small area, do not show as great a range in values as do those from locality 2.

	Range of Locality 1	Range of Locality 2
Li . .	6–12 ppm.	3–15 ppm.
Na . .	1,700–2,600 ppm.	1,400–2,700 ppm.
Rb . .	10–45 ppm.	8·5–60 ppm.
Cs . .	4–33 ppm.	5–35 ppm.
Rb/Cs . .	1–4·2 ppm.	0·47–3·5 ppm.

The members of genera common to both localities show few consistent differences (e.g. the *Dalmanites* from locality 2 has a much lower Li content than that from locality 1, while it is the *Acaste* from locality 1 that have less Li than that from locality 2). It would thus appear that, superimposed on a fairly high experimental error, there is a large variation range in these genera; this might be reduced considerably by making collections over a very small horizontal and vertical ranges of strata.

The specimens from the Wenlock Shale of Malvern appear in two

very distinct groups: *Encrinurus*, *Acaste*, and *Cheirurus* all have a high Li and a high Rb/Cs; *Acidaspis* and *Dalmanites* both have low Li content and a fairly low value of Rb/Cs, while *Deiphon* with a very low Rb/Cs and a moderate Li content is similar. The Dudley specimens all have intermediate values between these two Malvern groups, and thus once again the main difference between localities is one of range of variation. Another difference between the Malvern and Dudley collections is seen in the analyses of the *Acaste* and *Encrinurus* specimens: those from Malvern show higher values of Li and Rb/Cs than those from Dudley. The *Deiphon* from Malvern has the maximum Cs recorded in any trilobite (250 ppm.), although its matrix has only about 2 ppm. Cs.

The single specimen of *Calymene* from the algal reefs of the Woolhope Limestone at Old Radnor is worthy of special notice: though its Rb/Cs is normal (1·25), it has unusually high values of Rb, Cs, and Li (100, 80, and 25 ppm. respectively).

The Upper Caradocian cryptolithids (three specimens) and calymenid (one specimen) have high Rb/Cs values (above 5) and above average Li contents (more than 10 ppm.); they show much variation in the latter (*Onnia superba* has 50 ppm. Li). These high values serve to distinguish them from the Lower Caradocian specimens of *Trinucleus*, but not from the Lower Caradocian calymenid *Platycalymene duplicata* which, though having little Li, has a very high Rb/Cs value.

(*d*) *General Differences between Trilobites.*

It has been shown that there are some differences in the analyses of closely related forms from different localities; these differences are, however, very frequently changes in the range of variation rather than changes in mean values. So that, in spite of this variation from locality to locality, some general differences (possibly of genetic significance) between genera or families become apparent.

Paradoxides and *Deiphon* (low Rb/Cs) and *Asaphus* (low Li) appear to have some values so distinct from the rest of the analyses that they may be of genetic significance.

The cryptolithids from the Upper Ordovician show a progressive increase in Rb/Cs from *Trinucleus fimbriatus* (Lower Caradocian) through *Onnia sp.* (Upper Caradocian) to the Ashgillian form from Westmorland. The total ranges in Li and Rb/Cs seen in this family, however, are so great that they do not distinguish the group as a whole from other trilobite genera.

Of the Silurian trilobites analysed, *Acaste*, *Encrinurus*, *Cheirurus*, and *Deiphon* have higher mean values of Li than *Acidaspis* and *Dalmanites* (though some of these ranges of variation overlap to a

small extent); *Calymene* has too great a range of variation in Li to be distinctive. All the Silurian forms have large variation ranges in Rb/Cs and only *Deiphon* (with a very low value) is distinct from other contemporary genera in this respect.

In view of the small size of *Deiphon*, its spinose form has been considered by some authorities as an adaption to increase surface tension and thus assist in a pelagic mode of life (most other trilobites probably swam near the sea floor in shallow water). The unusual cesium enrichment in *Deiphon* (Cs 250 ppm.; Rb/Cs 0·36) cannot, however, be entirely explained by its different mode of life, as *Acidaspis* (another small spiny form, also thought to be pelagic) does not show more than average enrichment (Cs 8 ppm.; Rb/Cs 1·25). Another spinose form, *Paradoxides davidis*, has a very low Rb/Cs ratio (0·26) though it is not very rich in Cs (25 ppm.). This trilobite is large (6 inches or more in length), so the spines are not likely to be of much use in assisting flotation, and thus a low Rb/Cs value cannot always be associated with a pelagic mode of life. But the analyses of *Cheirurus*, a genus which is not excessively spinose and which belongs to the same family as *Deiphon*, show a much higher Rb/Cs ratio (5·0 as compared with 0·36), so the possibility remains that relative Cs enrichment may in this instance be associated with the adoption of a pelagic mode of life.

Analyses of Some Modern Arthropods

In addition to the twenty-eight trilobites discussed above, ten other arthropods have been analysed (Table 2). These include four crustaceans which all differ markedly from the trilobites in having less than 3 ppm. Cs and less than 1 ppm. Rb; some, however, have comparable amounts of Na and Rb, and the content of these last two elements is very different in the four forms analysed. *Homarus vulgaris*, a lobster occurring in British seas which is secondarily marine, has a higher Na content (4,700 ppm.) than any trilobite analysed, and it is distinct from the other three modern crustaceans in having 8 ppm. Li (about the same proportion as in the average trilobite). *Scyllarus latus*, a marine rock-lobster occurring in the Mediterranean, has 2,700 ppm. Na and 4 ppm. Li, values intermediate between *Homarus vulgaris* and *Astacus fluviatilis* (a river crayfish with 1,150 ppm. Na and 1 ppm. Li). It was perhaps to be expected that a non-marine form would have less of these elements in its skeleton, but it is of note that the warmer conditions of the Mediterranean do not result in higher values. A crab, *Carcinus maenas*, differs from the other three crustaceans in having 3 ppm. Cs (compared with less than 1 ppm.).

The four insects considered are three beetles and a cockroach, forms

with bodies large enough to provide sufficient material for analyses. They are all similar to the crab and the crayfish in having little Cs and Li (less than 1 ppm. and 0·3 ppm. respectively). The cockroach (*Periplaneta americana*) and one beetle (*Blaps mucronata*) are like all the modern aquatic arthropods in having less than 1 ppm. Rb. The three beetles each contain different proportions of Na and Rb: *Blaps* has less than 1 ppm. Rb and 1,300 ppm. Na, *Cetonia aurata* (a beetle from the New Forest) has 3·5 ppm. Rb and 820 ppm. Na, and a cetoniid from Uganda has about 2 ppm. Rb and only 680 ppm. Na (the lowest value for Na recorded in any arthropod). Here, as in the modern marine crustacea, the animal living in the warmer climate has least Na and little Li. The tropical *Periplaneta* also has little Li.

Two xiphosurids were analysed: the modern marine *Limulus* and the Carboniferous *Euproops* (probably non-marine). *Limulus* has no recognizable amounts of Rb, Cs, or Li (less than 1, 1, and 0·2 respectively), while *Euproops* has values similar to many trilobites (Rb 14 ppm., Cs 3 ppm., and Li 10 ppm.).

Comparison with Crustal Distribution

An inspection of the intensities of the K lines in the trilobite spectra shows that the ratio K/Rb cannot be markedly different from that in igneous rocks and sediments, where it is almost invariably constant except in extreme acid differentiates, pegmatites, etc. (Ahrens, Pinson, and Kearns, 1952). The Rb/Cs ratio is markedly different from those in igneous rocks and sediments and shows marked Cs enrichment.

For surface igneous rocks, Rankama (1954, Table 9–1) gave values 400 ppm. Rb and 5 ppm. Cs. The rubidium abundance was based on spectrographic data obtained using G-1 and W-1 as standards with the Rb values recommended by Ahrens (1954, Table 3–3). Work on these standards by Herzog and Pinson (1955) and Smales (1955) has shown that Ahrens' figure was about 2·5 times too large, so that Rankama's abundance estimate needs revising to about 160 ppm. Rb (Rb/Cs = 32).

Canney (1952) determined Rb and Cs in 323 sedimentary rocks and gave average values of 280 ppm. Rb and 7·5 ppm. Cs. Since Canney's Rb values for G-1 and W-1 by the same method were similar to those originally recommended, his Rb figure similarly needs adjusting to 110 ppm. (Rb/Cs = 15). Canney noted that Cs was enriched in sediments relative to Rb. Smales and Salmon (1955) have determined Rb and Cs in sea water finding 120 pp. 1,000 million Rb and 0·5 pp. 1,000 million Cs (Rb/Cs = 240).

The arithmetic mean of the Rb/Cs ratio for the trilobites is 3·9 and the geometric mean is 2·4. For the enclosing sediment, the arithmetic mean is 19 and the geometric mean 15.

REFERENCES

AHRENS, L. H., 1950. *Spectrochemical Analysis.* Cambridge, Mass.
—— 1954. *Quantitative spectrochemical analysis of silicates.* London.
—— PINSON, W. H., and KEARNS, M. M., 1952. Association of rubidium and potassium and their abundance in common igneous rocks and meteorites. *Geochim. et Cosmochim. Acta*, ii, 229–242.
BUTLER, A. J., 1940. The stratigraphy of the Wenlock Limestone of Dudley. *Quart. Journ. Geol. Soc.*, xcv, 37–74.
CANNEY, F. C., 1952. Some aspects of the geochemistry of potassium, rubidium, cesium, and thallium in sediments. *Bull. Geol. Soc. Amer.*, lxiii, 1238.
CHAVE, K. E., 1954. Aspects of the biogeochemistry of magnesium. I Calcareous marine organisms. *Journ. Geol.*, lxii, 266–283.
CLARKE, F. W., and WHEELER, W. C., 1922. The inorganic constituents of marine invertebrates. *U.S. Geol. Surv. Prof. Paper* 124.
FEARON, W. R., 1946. *Introduction to biochemistry.* London.
HEILBRUNN, L. V., 1952. *Outline of general physiology.* Philadelphia.
HERZOG, L. F., and PINSON, W. H., 1955. The Sr and Rb contents of the granite G-1 and the diabase W-1. *Geochim. et Cosmochim. Acta*, viii, 295–8.
KULP, J. L., TUREKIAN, K., and BOYD, D. W., 1952. Strontium content of limestones and fossils. *Bull. Geol. Soc. Amer.*, lxiii, 701–716.
LIPSON, J. I., 1956. K-A dating of sediments. *Geochim. et Cosmochim. Acta*, x, 149–151.
RICHARDS, A. G., 1951. *The integument of arthropods.* Minneapolis.
SMALES, A. A., 1955. Some trace-element determinations in G-1 and W-1 by neutron activation. *Geochim. et Cosmochim. Acta*, viii, 300.
—— and SALMON, L., 1955. Determination by radioactivation of small amounts of rubidium and cesium in sea water and related materials of geochemical interest. *Analyst*, 80, 37–50.
VINOGRADOV, A. P., 1953. The elementary composition of marine organisms. *Mem.* 2, *Sears Foundation for Marine Research*, New Haven, Conn.
WEBB, D. A., 1937. Studies of the ultimate composition of biological material. *Sci. Proc. Roy. Dublin Soc.*, xxi, 487–539.

DEPARTMENT OF GEOLOGY AND MINERALOGY,
OXFORD.

EXPLANATION OF PLATE XIII.

Alkali metal spectra of the trilobite *Deiphon* (A) and its enclosing matrix (B) showing the relative intensities of the K, Rb and Cs lines.

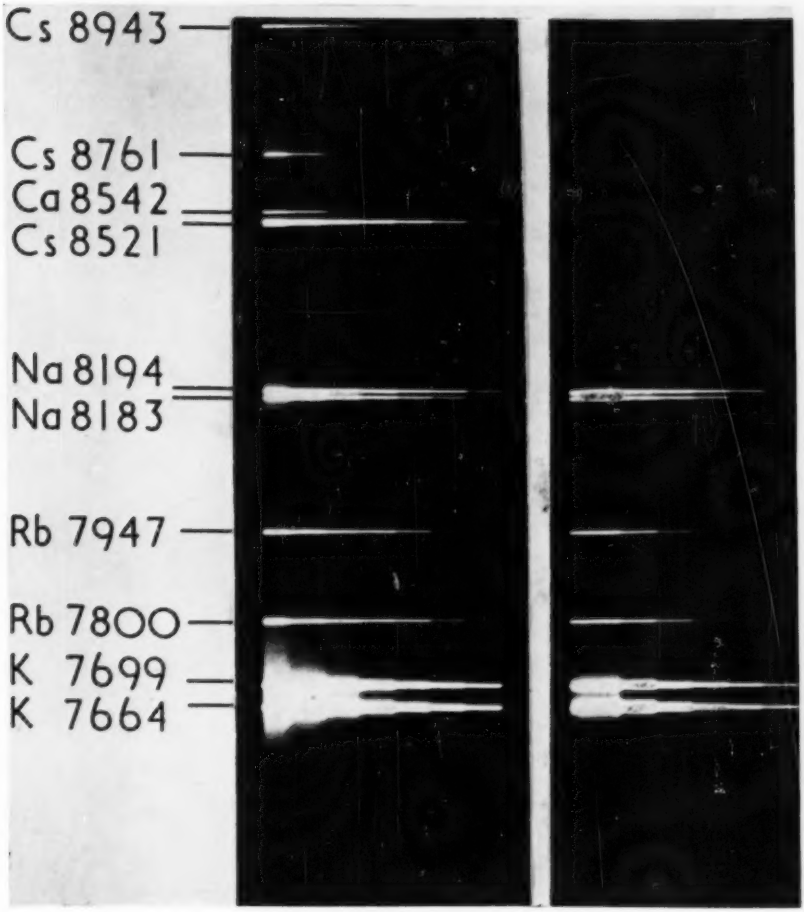
CORRESPONDENCE

THE ORIGIN OF GARNETS IN THE BORROWDALE VOLCANIC SERIES

SIR,—Dr. Firman's letter is to be welcomed as a justified comment on the writer's postulation of the "Borrowdale" garnet genesis which, though perhaps not obviously, also was submitted (*Geol. Mag.*, 1954, pp. 121–139) "with some trepidation". In the light of Dr. Firman's arguments, the writer feels the need to discuss the problem at greater length.

It is true that garnets are rare "in lavas of any age, composition, or history"; the writer is prepared to admit that the existence of special environmental conditions were perhaps necessary for the crystallization of the garnets (see further below).

Almandine garnets have not been synthesized at atmospheric or relatively low pressures, but they have recently been synthesized at moderately high pressures. Firman's contention that there is a lack of experimental evidence



Alkali metal spectra of A: *Deiphon*. B: matrix surrounding *Deiphon*

in support of the likelihood of almandine crystallizing from an andesitic magma is not supported by H. S. Yoder's recent work (*Amer. Min.*, xl, 1955, p. 342) on the almandine garnet stability curve which, according to Yoder, accounts for the occurrence of almandine in metamorphic rocks *as well as in some igneous rocks*. There is little doubt that the garnets (of similar composition to those in the Borrowdale volcanics) contained in, for example, the Dartmoor Granite are magmatic (see A. Brammall and H. F. Harwood, *Miner. Mag.*, xx, 1923, pp. 39–52), and pressures operating on the granite at the time of garnet crystallization are not likely to have been very much higher than those affecting the Borrowdale andesitic magma at depth.

Dr. Firman's statement that plagioclase coronas round many of the Lake District garnets are illustrative of xenocrystal garnets in disequilibrium with the magmatic liquid is not consistent with his contention that the garnets as xenocrysts free to react with the liquid might be expected to vary in composition sympathetically with the composition of the containing rock.

The closest comparison to the " Borrowdale " garnets and their environment is, as far as the writer is aware, those contained in dacitic and rhyodacitic lavas in Victoria, Australia, discussed in a number of papers by Dr. A. B. Edwards and other workers. Edwards (*Proc. Roy. Soc. Victoria*, xlix, 1936, p. 40) admits the possibility that the Victorian garnetiferous rocks are syntectics—in other words, that they have been contaminated—and the same view is held by other Australian investigators. The presence of garnets, already mentioned, in the Dartmoor Granite is attributed by Brammall and Bracewell (*Nature*, cxxxi, 1933, p. 250) to contamination by the country rock. These examples, and also several others, indicate that a higher relative proportion of alumina than can be attained by " internal " magmatic differentiation is apparently necessary for the crystallization of almandine garnets. In the Lake District, the Skiddaw Slates, underlying the Borrowdale volcanics, are a not impossible source of aluminous material.

The writer considers it quite probable that assimilation of aluminous sediment (or metamorphosed sediment) has facilitated the crystallization of the " Borrowdale " garnets. Such an explanation would account for the rather random and patchy distribution of the garnets emphasized by Dr. Firman, though it would still be compatible with the restriction of the garnets to lavas of a limited compositional range (maintained by the writer). The absence in the lavas of definite and recognizable xenocrysts or xenoliths from metamorphic rocks does not support Dr. Firman's contention that the garnets are xenocrysts from metamorphic garnetiferous rocks at depth; nor is the suggestion that welded tuffs in the Lake District are a significant host and associate of the garnetiferous rocks substantiated by the non-occurrence of garnets in most welded tuffs recorded elsewhere.

R. L. Oliver.

c/o Photographic Survey Corporation,
P.O. Box 1339,
Colombo, Ceylon.
9th October, 1956.

THE AMMONITE GENERA *ARNIOCERAS* AND *CORONICERAS* HYATT

Sir,—In his account of the Liassic ammonites of the Stowell Park boring, published summer, 1956, Dr. Spath makes incorrect statements as to the type species of the above genera. In view of Dr. Spath's high authority on Liassic ammonites it is desirable to point this out in case other authors are misled into erroneous concepts of the genera.

Arnioceras Hyatt, 1867.—Dr. Spath (1956, p. 151) states that the type species " remains *A. ceratitoides* (Quenstedt) ". Apart from any question as to the identity of this species, the type species of the genus *Arnioceras*

has been designated by the International Commission on Zoological Nomenclature under its plenary powers as *A. cuneiforme* Hyatt, 1867 (Opinion 307, published 6th December, 1954).

Coroniceras Hyatt, 1867.—Dr. Spath (1956, p. 157) states that Buckman (1898, p. 459) " must be " considered to have selected *Amm. rotiformis* as type of *Coroniceras*. The facts are that *Coroniceras*, with many other genera, appeared in Buckman's (1898) notorious List of Genera, in which each genus is followed by one or more illustrative species, with the remark " *In most cases* the name which stands first *may be* considered as the type of the genus " (our italics). Article 30, IIg, of the Rules lays down : " The meaning of the expression ' select the type ' is to be rigidly construed. Mention of a species as an illustration or example of a genus does not constitute a selection of a type." In case there should be any doubt of the decision by most palæontologists concerned to set aside Buckman's 1898 List, as not containing valid type selections, it is only necessary to refer to Buckman's own explanation of it. Buckman wrote (1924, p. 34) : " Dr. Spath (1924, p. 202) says that I selected *Am. rotiformis* as genotype [of *Coroniceras*] in my 1898 paper. This is a mistake on his part : I particularly desired to avoid making any definite selection of genotypes. My phrase merely states possibilities : it is not positive . . . Had it said : In all cases the name which stands first is to be considered as the type species—it would have been a different matter."

In any case, the genus *Coroniceras* has been added to the Official List of Generic Names in Zoology by the International Commission with type species *Ammonites kridion* Hehl MS. in Zieten, as validly designated by Bonarelli in 1900 (Opinion 324, published 7th January, 1955). The original figured specimen of *Amm. kridion* has been refigured by Walliser (1956, p. 200, pl. 10, fig. 5) who maintains that it represents the inner whorls of an *Amm. rotiformis* J. de C. Sowerby ; but even if this is so, *Amm. kridion* remains the nominal type species.

W. J. Arkell.
D. T. Donovan.

REFERENCES

Buckman, S. S., 1898. *Quart. Journ. Geol. Soc.*, liv, 442.
—— 1924. *Type Ammonites*, v, 34.
Spath, L. F., 1924. *Proc. Geol. Assoc.*, xxxv, 186.
—— 1956. *Bull. Geol. Surv. Gt. Brit.*, xi, 140.
Walliser, O. H., 1956. *Abh. Neues Jb. Geol. Pal.*, ciii, 181.
Opinions 307 (1954), *324* (1955). Opinions and Declarations Rendered by the International Commission on Zoological Nomenclature, vol. 8, part 24, p. 323 ; vol. 9, part 15, p. 227.

STEINERINA Hudson, nom. nov.

Sir,—The name *Steineria* proposed by me (Hudson, 1956, p. 722) for a genus of Jurassic hydroids of the family Milleporidiidae is preoccupied by *Steineria* Micoletzky, 1922, p. 119, a subgenus of nematode worm. I therefore replace the generic name *Steineria* Hudson, 1956 (type species of genus : *Stromatopora romanica* Dehorne) by *Steinerina* nom. nov.

R. G. S. Hudson.

REFERENCES

Micoletzky, H., 1922. Die freilebenden Erd-Nematoden. *Archiv für Naturgeschichte*, Jhrg. 87 (for 1921), Abt. A, hefts 8, 9, 1–320, 320a, b, 321–650. (March, 1922.)
Hudson, R. G. S., 1956. Tethyan Jurassic Hydroids of the family Milleporidiidae. *Journ. Paleont.*, 30, 714–730.

Department of Geology,
Iraq Petroleum Company, Ltd.,
214 Oxford Street,
London, W. 1.

8th November, 1956.

PUBLICATIONS RECEIVED

LIVERPOOL AND MANCHESTER GEOLOGICAL JOURNAL, Vol. 1, pt. 5. Papers by E. B. Bailey, J. C. Harper, G. H. Mitchell, and F. W. Shotton. pp. 420–65, with 5 plates. Liverpool Letterpress, Ltd., 1956.

GEOLOGICAL SURVEY OF GT. BRITAIN. *Summary of Progress for the Year 1955.* pp. iv + 87. London, H.M.S.O., 1956. Price 4*s.* 6*d.*

GEOLOGICAL SURVEY OF GT. BRITAIN, BULLETIN No. 11. Papers by G. W. Green, R. V. Melville, D. R. A. Ponsford, W. Bullerwell, and L. F. Spath. pp. iv + 164, with 10 pls. London, H.M.S.O., 1956. Price 17*s.* 6*d.*

E. M. GUPPY (with petrographical descriptions by P. A. Sabine). *Chemical Analyses of Igneous Rocks, Metamorphic Rocks and Minerals 1931–1954.* Memoirs of the Geological Survey of Great Britain. H.M. Stationery Office, 1956. pp. v + 78. Price 10*s.* 6*d.*

H. G. DINES (with petrographical notes by J. PHEMISTER). *The Metalliferous Mining Region of South-West England.* Memoirs of the Geological Survey of Great Britain. 2 Vols. H.M. Stationery Office, 1956. pp. viii + 508 and vi + 286, with 15 pls. + 14 maps. Price £5 5*s.*

CYPRUS. GEOLOGICAL SURVEY DEPARTMENT. *Annual Report for 1955.* By F. T. Ingham. Cosmos Press, Ltd., Nicosia, 1956. pp. 1–40, with tables, figs., and maps. Price 100 mils. (2*s.*).

BECHUANALAND PROTECTORATE, GEOLOGICAL SURVEY DEPARTMENT. *Annual Report for 1955.* 46 pp., with tables, figs., and map. Price 3*s.*

FEDERATION OF NIGERIA. *Annual Report of the Geological Survey Department for 1954–55.* Federal Government Printer, Lagos, 1956. 13 pp. Price 9*d.*

FEDERATION OF NIGERIA, *Geological Survey Department.* Geological Map of Nigeria (in colour), scale 1 : 2,000,000. (No price.)

NORTHERN RHODESIA. *Department of Geological Survey, Annual Report for 1955.* Government Printer, Lusaka, 1956. 10 pp. Price 2*s.*

SOUTHERN RHODESIA. *Report of the Director Geological Survey for 1955.* Government Printer, Salisbury, 1956. 11 pp.

SOUTH AFRICA, *Geological Society. Some aspects of the Geomorphology of Central and Southern Africa* (du Toit Memorial Lecture No. 4). By F. Dixey. Horters, Ltd., Johannesburg. 58 pp., with 12 figs. (No price.)

FIJI LEGISLATIVE COUNCIL, *Annual Report of Geological Survey for 1955.* Government Press, Suva, 1956. 11 pp.

AUSTRALIA. *Memoirs of the National Museum of Victoria*, No. 19 (Geology and Zoology). Government Printer, Melbourne, 1955. 163 pp., with 18 pls. and numerous text-figs.

AUSTRALIA. *Memoirs of the National Museum of Victoria*, No. 20 (Geology, Zoology, and Anthropology). Government Printer, Melbourne, 1956. 203 pp., with numerous figs. and pls.

AUSTRALIA. *Records of the Queen Victoria Museum, Launceston.* New Series, No. 6. Cainozoic History of Mowbray Swamp and Other Areas of North-Western Tasmania. By E. D. Gill and M. R. Banks. Government Printer, Tasmania, 1956. 42 pp., with 7 pls. and 6 text-figs.

CANADA. *Geological Survey of Canada, Bulletin 28.* Pelecypoda of the Ottawa Formation of the Ottawa–St. Lawrence Lowland. By A. E. WILSON. Ottawa, 1956. pp. v + 102, 9 pls. Price 50 cents.

CANADA. *Geological Survey of Canada, Memoir 280.* Uppermost Cretaceous and Paleocene non-marine Molluscan faunas of Western Alberta. By E. T. TOZER. Ottawa, 1956. pp. v + 125, 9 pls. Price One Dollar.

CANADA. *Geological Survey of Canada, Memoir 281.* Stratigraphy and Palaeontology of the Interlake Group and Stonewall Formation of Southern Manitoba. By C. W. STEARN. Ottawa, 1956. pp. iv + 162, with 16 pls. Price One Dollar.

H. P. SMITH. *Foraminifera from the Wagonwheel Formation, Devils Den District, California.* University of California Press, 1956. pp. 65–126, pls. 9–16, and 3 figs. Price $1.50.

L. M. J. U. VAN STRAATEN. *Composition and structure of recent marine sediments in the Netherlands.* Leidse Geologische Mededelingen, 1954. 108 pp., with 12 pls. and 26 figs. (No price.)

PERU. *Anuario de la Industria Minera del Perú en 1954, Boletin* No. 14. Ministerio de Fomento Y Obras Publicas, Lima, 1955. pp. xvi + 294, and tables.

PERU. *La Geologia de la Region Casca — Junin. La Geologia del valle del Rio Mantaro.* By J. V. Harrison. *La Geologia entre Macusani y Ollachea.* By G. H. Francis. *Boletin* No. 15, Ministerio de Fomento y Obras Publicas, Lima, 1956. pp. 75, and maps.

PERU. *Los Yacimientos de Plomo y Zinc de la Region de Rio Pallanga.* By R. F. Johnson and A. Manrique. *Los Depositos Minerales de la Provincia de Cajatambo.* By R. W. Lewis and S. Narvaez. *Boletin* No. 13, Ministerio de Fomento y Obras Publicas, Lima, 1955. pp. 43 and maps.

YUGOSLAVIA. *Geološki Vjesnik* (*Bulletin Géologique*), Tome VIII–IX, 1954–5. Zagreb, 1956.

POLAND. *Annales de la Société Géologique de Pologne*, Vol. XXIV, Fasc. 2–3. The Jurassic and Cretaceous of Bachowice. By M. Ksiazkiewicz. Kraków, 1956. pp. 121–405, pl. xi–xxxii, 61 figs.

EGYPT. *Abstracts of the Proceedings of the Geological Society of Egypt. Vol. 1*, No. 1, pp. 1–37. Cairo, 1955; *Vol. 2*, No. 1, pp. 1–18. Cairo, 1956.

J. C. SWAYNE. *A concise Glossary of Geographical Terms.* G. Phillip & Son, Ltd. London, 1956. pp. vii + 164. Price 6*s*. 6*d*.

H. G. SMITH. *Minerals and the Microscope.* Thomas Murby & Co., London, 1956. 4th Edition (revised by M. K. WELLS). pp. 148, with 12 pls., and 23 figs. Price 12*s*. 6*d*.

N. L. BOWEN. *The Evolution of the Igneous Rocks.* (With a new introduction by J. F. Schairer.) Dover Publications, Inc., New York, 1956. 332 pp. Price $1.85.

F. C. PHILLIPS. *An Introduction to Crystallography.* Longmans, Green & Co., London, 1956. 2nd Edition. pp. ix + 324, with 515 figs. Price 30*s*.

Commemorative Volume dedicated to Dr. S. TSUBOI. Tokyo, 1955. pp. x + 479, with pls., figs., and maps.

E. S. LARSEN Jr. and WHITMAN CROSS. *Geology and Petrology of the San Juan Region Southwestern Colorado.* U.S. Geological Survey, Prof. Paper 258, 1956. pp. xiv + 303, maps and 58 figs.

ANNOUNCEMENT

The Fifth International Congress of the International Association on Quaternary Research (INQUA) is to be held in Spain (Madrid and Barcelona) in 1957 between 20th September and 3rd October. Communications and enquiries should be addressed to :—

Señor L. Solé Sabarís,
Instituto Geologico,
Universidad,
Barcelona.

THE INDEX

TO THIS VOLUME HAS BEEN REMOVED FROM THIS POSITION AND PLACED AT THE BEGINNING OF THE FILM FOR THE CONVENIENCE OF READERS.

L. M. J. U. VAN STRAATEN. *Composition and structure of recent marine sediments in the Netherlands.* Leidse Geologische Mededelingen, 1954. 108 pp., with 12 pls. and 26 figs. (No price.)

PERU. *Anuario de la Industria Minera del Perú en 1954, Boletin* No. 14. Ministerio de Fomento Y Obras Publicas, Lima, 1955. pp. xvi + 294, and tables.

PERU. *La Geologia de la Region Casca — Junin. La Geologia del valle del Rio Mantaro.* By J. V. Harrison. *La Geologia entre Macusani y Ollachea.* By G. H. Francis. *Boletin* No. 15, Ministerio de Fomento y Obras Publicas, Lima, 1956. pp. 75, and maps.

PERU. *Los Yacimientos de Plomo y Zinc de la Region de Rio Pallanga.* By R. F. Johnson and A. Manrique. *Los Depositos Minerales de la Provincia de Cajatambo.* By R. W. Lewis and S. Narvaez. *Boletin* No. 13, Ministerio de Fomento y Obras Publicas, Lima, 1955. pp. 43 and maps.

YUGOSLAVIA. *Geološki Vjesnik* (*Bulletin Géologique*), Tome VIII–IX, 1954–5. Zagreb, 1956.

POLAND. *Annales de la Société Géologique de Pologne*, Vol. XXIV, Fasc. 2–3. The Jurassic and Cretaceous of Bachowice. By M. Ksiazkiewicz. Kraków, 1956. pp. 121–405, pl. xi–xxxii, 61 figs.

EGYPT. *Abstracts of the Proceedings of the Geological Society of Egypt. Vol. 1*, No. 1, pp. 1–37. Cairo, 1955; *Vol. 2*, No. 1, pp. 1–18. Cairo, 1956.

J. C. SWAYNE. *A concise Glossary of Geographical Terms.* G. Phillip & Son, Ltd. London, 1956. pp. vii + 164. Price 6*s.* 6*d.*

H. G. SMITH. *Minerals and the Microscope.* Thomas Murby & Co., London, 1956. 4th Edition (revised by M. K. WELLS). pp. 148, with 12 pls., and 23 figs. Price 12*s.* 6*d.*

N. L. BOWEN. *The Evolution of the Igneous Rocks.* (With a new introduction by J. F. Schairer.) Dover Publications, Inc., New York, 1956. 332 pp. Price $1.85.

F. C. PHILLIPS. *An Introduction to Crystallography.* Longmans, Green & Co., London, 1956. 2nd Edition. pp. ix + 324, with 515 figs. Price 30*s.*

Commemorative Volume dedicated to Dr. S. TSUBOI. Tokyo, 1955. pp. x + 479, with pls., figs., and maps.

E. S. LARSEN Jr. and WHITMAN CROSS. *Geology and Petrology of the San Juan Region Southwestern Colorado.* U.S. Geological Survey, Prof. Paper 258, 1956. pp. xiv + 303, maps and 58 figs.

ANNOUNCEMENT

The Fifth International Congress of the International Association on Quaternary Research (INQUA) is to be held in Spain (Madrid and Barcelona) in 1957 between 20th September and 3rd October. Communications and enquiries should be addressed to :—

Señor L. Solé Sabarís,
Instituto Geologico,
Universidad,
Barcelona.

THE COALFIELDS OF GREAT BRITAIN

Edited by

SIR ARTHUR TRUEMAN, K.B.E., D.Sc., F.R.S.

" . . . a first-class work of reference characterized by its comprehensiveness, its authority, its clarity of plan and expression, and above all by a most exceptional feature in a textbook—its remarkable up-to-dateness."—*Geological Magazine.*

408 pages, 106 illustrations, 7 plates. 63*s.* net

A GEOLOGY FOR ENGINEERS

F. G. H. BLYTH, Ph.D., M.Sc., A.C.G.I., F.G.S.

" . . . This is in every respect a scholarly and scientific production, fully documented, illustrated, and referenced, and with a list of books at the end of each chapter for further study. An excellent index increases its value as a work of reference."—*Surveyor.*

344 pages, 16 plates, 141 diagrams. 25*s.* net

EDWARD ARNOLD

AUSTRALIA—UNIVERSITY OF MELBOURNE

Applications are invited for a position of SENIOR LECTURER or LECTURER IN GEOLOGY. The lecturer may be required to lecture on elementary general geology and special knowledge of mineralogy, economic geology, or similar subjects would be desirable.

The salary will be determined according to qualifications and experience in the following ranges :—

Senior Lecturer :	£A1,850 to £A2,150 per annum
Lecturer :	£A1,300 to £A1,800 per annum

Superannuation similar to F.S.S.U. will be provided.

Further particulars and information as to the method of application may be obtained from the Secretary, Association of Universities of the British Commonwealth, 36 Gordon Square, London, W.C. 1.

The closing date for the receipt of applications, in Australia and London, is *31st December, 1956.*